FUZZY LOGIC CONTROL TYPE-2 IN NETWORKED CONTROL SYSTEMS

BY

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بسم الله الرحمن الرحيم

I lovingly dedicate this thesis to my MOM, sister and all my wonderful friends

for their love, support, encouragement.

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LIST OF ABBREVIATIONS

NCS – Networked Control Systems

FLC – Fuzzy Logic Controller

FLS – Fuzzy Logic System

TS – Takagi Sugeno

MF – Membership Function

KM Method – Karnik Mendel Method

ABSTRACT

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Networked Control Systems have been a very popular area of research for the past decade in academics as well as in the industry. Transfer of data in the network may sometimes be hindered due to variable time delays induced by the network and data packet dropouts. Various control strategies are being developed over the years to deal with the aforementioned problem.

The trend of moving from traditional centralized control to distributed control has led to the change in the design of the control systems and thereby leading to the development of the concept of Networked Control Systems. Despite of the advantages of NCS, data transfer between two points in the network may induce network delays. The other problem is that of data packet dropout.

Many control strategies have been developed to deal with the losses. Fuzzy logic is a widely used control technique. The type-1 FLS is most commonly used FLS. But the type-1 FLS is not suitable to deal with uncertainty in the process. This led to the development of type-2 FLC. It is better equipped at handling uncertainties in the system.

In this thesis, a nonlinear Networked Control System with delays is considered. To deal with the uncertainty in the network, an observer based type-2 Fuzzy Logic Controller is designed. First, a state feedback controller is studied based on type-2 Fuzzy Logic. Then an observer based fuzzy controller is designed based on Lyapunov Krasovskii theory. The effectiveness of the technique will be illustrated with the help of an example. The results of Type-2 FLC are then compared with Type-1 FLC to prove the effectiveness of the control technique.

ملخص الرسالة

الاسم الكامل : محمد مدثر

عنوان الرسالة : النوع الثانى من تحكم المنطق المائع لشبكة أنظمة

التخصص : هندسة نظم

تاريخ الدرجة العلمية : ديسمبر 2014

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الاتجاة للتحرك من التحكم المركزى الى التحكم الموزع أدى لتغير فى تصميم النظم ومن ثم أدى لتوليد مبدأ تحكم شبكات الأنظمة. بالرغم من مميزات شبكات التحكم الا ان نقل البيانات بين مركزين ممكن ينتخ تأخير. المشكلة الاخرى هو الفقد فى البيانات.

العديد من اهداف التحكم طورت لتتعامل مع المفقودات. المنطق العائم استخدم فى تقنيات التحكم. النوع الأول غير مناسب ليتعامل مع عدم الثبات فى العملية. هذا أدى لتطوير النوع الثانى من التحكم المنطقى العائم. من الأفضل التعامل مع عدم الثبات فى الأنظمة.

فى هذة الرسالة تحمك شبكى غير خطى مع تأخير استخدم. للتعامل مع عدم الثبات, ملاحظ صمم بناء على تحكم النطق الحائم. أول تحكم تغية رجعى درس النوع الثانى من المنطق العائم. ثم صمم

الملاعظ مستندا على تحكم مائع ونظرية العالم ليابونوف. متانة التقنية سوف توضح مع أمثلة مساعدة. نتائج المتحكم الثانى ستقارن مع النوع الأول لأثبات متانة التحكم المستخدم.

INTRODUCTION

1.1 Networked Control Systems: An Overview

A Networked Control System can be defined as a traditional feedback control system which is closed by a communication channel like a network, which can be shared with different nodes other than the ones in the control system. Networked Control System (NCS) is basically a control system where sensors and actuators are connected to a feedback controller through a shared communication medium. There are many advantages of this approach like low cost, installation and maintenance is simple, drastic reduction in system wiring, and increase in the agility of the system which has led to more research in this field. However, the introduction of network for connecting sensors, actuators and controllers resulted in various issues like delays, packet dropouts, limited communication capacity, packet transmission scheduling, etc. This may result in inaccuracy in the information transmission or limited data transmissions which may finally lead to the degradation in the performance of the control system and can even make the system unstable [1-4].

Networked control systems are control systems comprised of the system to be controlled and of actuators, sensors, and controllers, the operation of which is coordinated via a shared communication network. These systems are typically spatially distributed, may operate in an asynchronous manner, but have their operation coordinated to achieve desired overall objectives. Research on Networked control systems (NCS) has been the prime focus both in academia and in industrial applications for several decades. In this chapter, we provide an introduction to NCS and the Fuzzy Logic Controllers. The chapter begins with the history of NCS, different advantages of having such systems. As we proceed further, the chapter gives an insight to different challenges faced with building efficient, stable and secure NCS. The following chapters provide a brief literature survey concerning each topic highlighting the recent trends in the evolution networked control systems.

As most of the physical systems and processes are nonlinear, an effective approach to deal with the nonlinear control systems is essential and fuzzy logic is best suited for this task. There is a growing interest in the (TS) fuzzy-model-based control used for complex nonlinear systems which provides basis for systematic stability analysis and design of controller for (TS) fuzzy control systems [5, 6].

For many years researchers have given us precise and optimum control strategies emerging from classical control theory, starting from open-loop control to sophisticated control strategies based on genetic algorithms. The advent of communication networks, however, introduced the concept of remotely controlling a system, which gave birth to networked control systems (NCS). The classical definition of NCS can be as follows: When a traditional feedback control system is closed via a communication channel, which may be shared with other nodes outside the control system, then the control system is called an NCS. An NCS can also be defined as a feedback control system wherein the control loops are closed through a real-time network. The defining feature of an NCS is that information (reference input, plant output, control input, etc.) is exchanged using a network among control system components (sensors, controllers, actuators, etc.), see Figure 1.

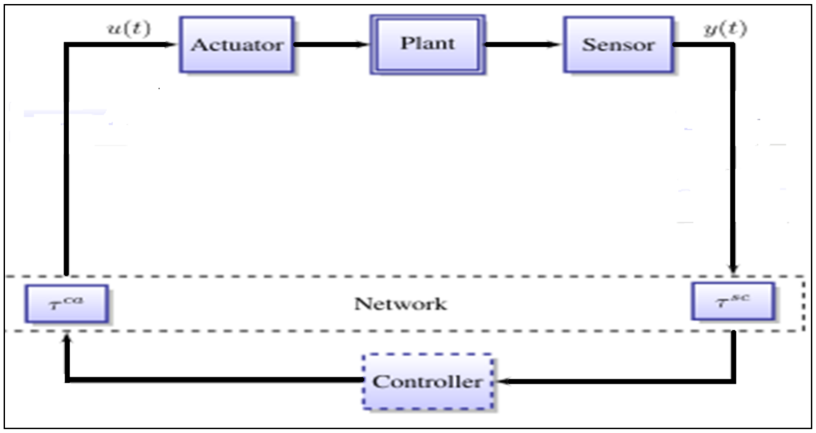

Figure 0.1: A typical representation of a Networked Control System [7]

1.2 Advantages of Networked Control Systems

For many years now, data networking technologies have been widely applied in industrial and military control applications. These applications include manufacturing plants, automobiles, and aircraft. Connecting the control system components in these applications, such as sensors, controllers, and actuators, via a network can effectively reduce the complexity of systems, with nominal economical investments. Furthermore, network controllers allow data to be shared efficiently. It is easy to fuse the global information to take intelligent decisions over a large physical space. They eliminate unnecessary wiring. It is easy to add more sensors, actuators and controllers with very little cost and without heavy structural changes to the whole system. Most importantly, they connect cyber space to physical space making task execution from a distance easily accessible (a form of tele-presence). NCSs have been finding application in a broad range of areas such as mobile sensor networks [7], and automated highway systems and unmanned aerial vehicles [8, 9]. Due to other advantages, such as low cost of installation, ease of maintenance and great flexibility, networked control systems (NCSs) have been widely used in DC motor systems, dual-axis hydraulic positioning systems, and large scale transportation vehicles etc.

One of the biggest advantages of a system controlled over a network is scalability. As we talk about adding many sensors connected through the network at different locations, we can also have one or more actuators connected to one or more controllers through the network. For many years now, researchers have given us precise and optimum control strategies emerging from classical control theory, starting from PID control, optimal control, adaptive control, robust control, intelligent control and many other advanced forms of these control algorithms.

1.3 Drawbacks of NCS

NCSs lie at the intersection of control and communication theories. The classic control theory focuses on the study of interconnected dynamical systems linked through “ideal channels”, whereas communication theory studies the transmission of information over “imperfect channels”. A combination of these two frameworks is needed to model NCSs. We can broadly categorize NCS applications into two categories as (1) time-sensitive applications or time-critical control such as military, space and navigation operations; (2) time-insensitive or non-real-time control such as data storage, sensor data collection, e-mail, etc. However, network reliability is an important factor for both types of systems. After having an overview of different categories, components and applications of NCS, let us discuss the key issues that make NCSs distinct from other control systems from a controls perspective.

Any communication network can only carry a finite amount of information per unit of time. In many applications, this limitation poses significant constraints on the operation of NCSs. Examples of NCSs that are afflicted by severe communication limitations include unmanned air vehicles (UAVs), due to stealth requirements, power-starved vehicles such as planetary rovers, long-endurance energy-limited systems such as sensor networks, underwater vehicles, and large arrays of micro-actuators and sensors.

To transmit a continuous-time signal over a network, the signal must be sampled, encoded in a digital format, transmitted over the network, and finally the data must be decoded at the receiver side. This process is significantly different from the usual periodic sampling in digital control. The overall delay between sampling and eventual decoding at the receiver can be highly variable because both the network access delays (i.e., the time it takes for a shared network to accept data) and the transmission delays (i.e., the time during which data are in transit inside the network) depend on highly variable network conditions such as congestion and channel quality. In some NCSs, the data transmitted are time stamped, which means that the receiver may have an estimate of the delays duration and take appropriate corrective action. A significant number of results have attempted to characterize a maximum upper bound on the sampling interval for which stability can be guaranteed. These results implicitly attempt to minimize the packet rate that is needed to stabilize a system through feedback.

A significant difference between NCSs and standard digital control is the possibility that data may be lost while in transit through the network. Typically, packet dropouts result from transmission errors in physical network links (which is far more common in wireless than in wired networks) or from buffer overflows due to congestion. Long transmission delays sometimes result in packet reordering, which essentially amounts to a packet dropout if the receiver discards ”outdated” arrivals. Reliable transmission protocols, such as TCP, guarantee the eventual delivery of packets. However, these protocols are not appropriate for NCSs since the retransmission of old data is generally not very useful. Normally feedback-controlled plants can tolerate a certain amount of data loss, but it is essential to determine whether the system is stable when only transmitting packets at a certain rate, and to compute the acceptable lower bounds on the packet transmission rates.

1.4 Fuzzy Logic Controller

Fuzzy Logic Controllers are basically formed using type-1 fuzzy sets [10] commonly known as type-1 FLCs. These controllers are used in various areas [11], specifically for controlling complex nonlinear systems which are very difficult for analytical modeling [12, 13]. In spite of the popularity of FLCs, research has proved that they are difficult to model and the effect of uncertainties is not easy to minimize [14, 15]. It is improbable for the plant model to fully integrate the actual plant characteristics, the performance of the controller designed by using this model will eventually deteriorate when applied to a practical system.

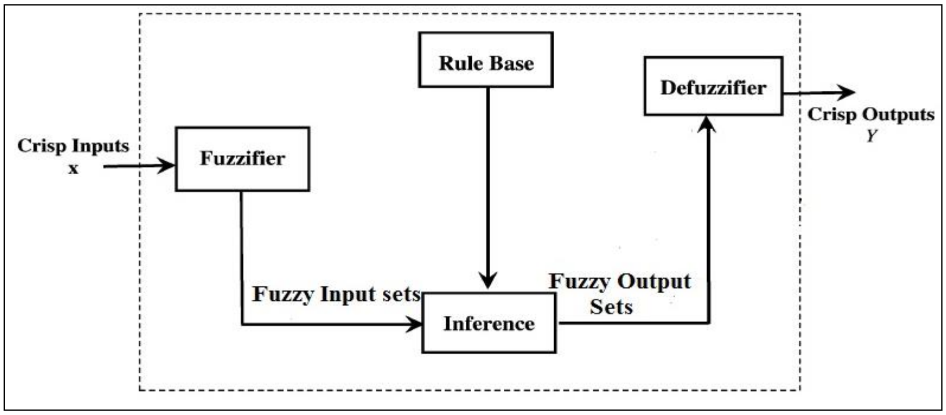

Figure 0.2: Type-1 Fuzzy Logic System

The Fuzzy Logic System (FLS) may be defined as the nonlinear mapping of an input data set to a scalar output data. The type-1 FLS is the most commonly used FLS. It basically contains the fuzzifier, the inference mechanism, the rules and the defuzzifier. The process of type-1 fuzzy logic can be explained as shown in Figure 1-2, a crisp set of input data are converted to a fuzzy set by fuzzy linguistic variable, fuzzy linguistic terms and membership functions. This step is known as fuzzification. Then, an inference is made based on the set of rules. The resulting fuzzy output is mapped to a crisp output using the membership functions in the defuzzification step. The membership function of type-1 fuzzy system can be depicted as shown in figure 3a.

The rules signify the relation between input and output. The most basic rules have multiple inputs and single output. For p inputs and one output we can write lth rule as [14]

$$R^l: \text{IF } x_1 \text{ is } X_1 \text{ and} \ldots \text{ and } x_p \text{ is } X_p \text{ THEN } y \text{ is } G^l, \;\; l = 1.....,r$$

where, r is number of rules. $X_{1.....,}X_p$ and G are the type-1 membership functions. The type-1 fuzzy set A, can be characterized by the membership function,

$$A = \{(x, \mu_A(x)) \mid \forall x \in X\}$$

μ_A have the constraints from 0 to 1 for $x \in X$.

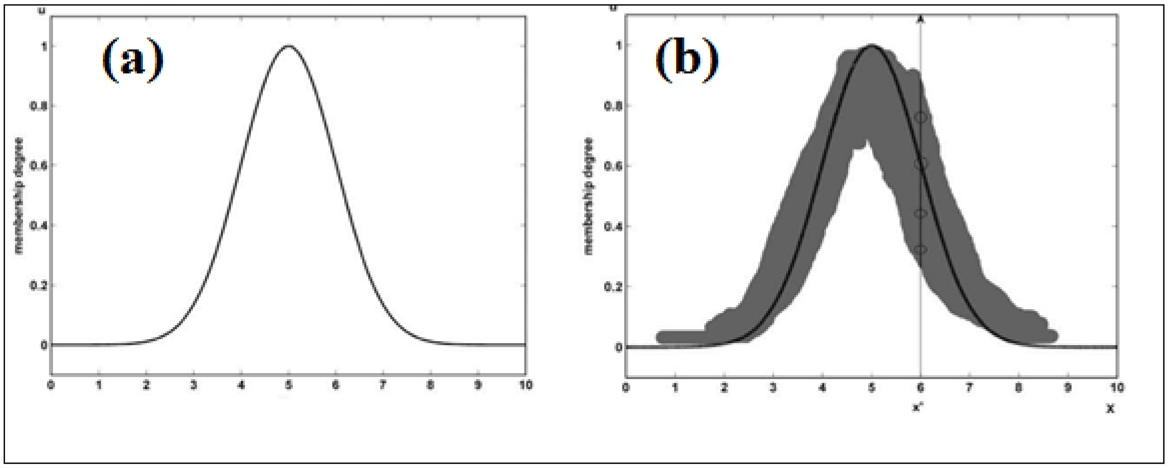

Figure 0.3: (a) Type-1 membership function, (b) Blurred Type-1 membership function [16]

Type-2 fuzzy sets were first introduced by Zadeh in 1975 [16] for better handling the uncertainties. In fuzzy type-2 sets the uncertainty is represented as an extra dimension. Figure 4 shows the typical structure of a type-2 FLC. Type-2 fuzzy sets are an extension of type-1 fuzzy sets in which uncertainty is represented by an additional dimension, as shown in figure 3. This extra third dimension in type-2 fuzzy logic systems (FLS) gives more degrees of freedom for better representation of uncertainty compared to type-1 fuzzy sets. Type-2 fuzzy sets are useful in circumstances where it is difficult to determine the exact membership function for a fuzzy set.

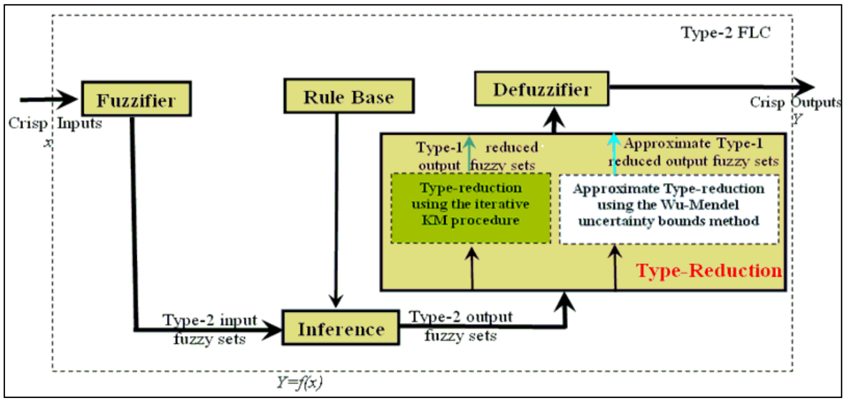

Figure 0.4: Type-2 Fuzzy Logic System

The Type-2 FLC is depicted in Figure (4) and it consists of a Fuzzifier, Inference Engine, Rule Base, Type-reducer and Defuzzifier. The crisp inputs from the input sensors are first fuzzified into input interval type-2 fuzzy sets. Singleton fuzzification (where the input value is represented by precise crisp value) is usually used in interval type-2 FLC applications due to its simplicity and suitability for embedded processors and real-time applications. The input interval type-2 fuzzy sets then activate the inference engine and the rule base to produce output interval type-2 fuzzy sets. The inference engine combines the fired rules and gives a mapping from input interval type-2 fuzzy sets to output interval type-2 fuzzy sets. The interval type-2 fuzzy outputs of the inference engine are then processed by the type-reducer, which combines the output sets and performs a centroid calculation that leads to type-1 fuzzy sets called the type-reduced sets. In the interval type-2 FLCs used so far, there are two ways to perform type-reduction: using the iterative Karnik-Mendel (KM) procedure to calculate the type-reduced fuzzy sets or using the Wu-Mendel uncertainty bounds method to approximate the type-reduced set. After the type-reduction process, the type-reduced sets (or approximate type-reduced sets) are then defuzzified (by taking the average of the type-reduced/approximated type-reduced set) to obtain crisp outputs that are sent to the actuators.

If we have a type-1 membership function, as in Fig. 3a, and we are blurring it to the left and to the right, as illustrated in Fig. 3b, then, for a specific value x', the membership function (u'), takes on different values, which are not all weighted the same, so we can assign an amplitude distribution to all of those points. Doing this for all $x \in X$, we create a three-dimensional membership function – a type-2 membership function that characterizes a type-2 fuzzy set. [42,43]. The input for type-2 FLC is any crisp input like a feedback error or it can be multiple inputs as feedback error and change of error, the output is any crisp output like change in control signal in a system.

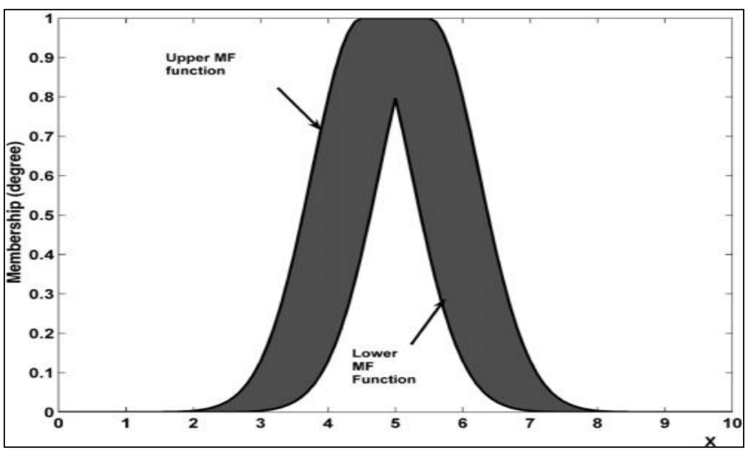

Figure 0.5: Type-2 membership function [17]

Rules of type-2 FLS have type-2 fuzzy sets for *p* inputs and one output is given as,

R^l: IF x_1 is $\tilde{X}_1$ and… and x_p is $\tilde{X}_p$ THEN y is $\tilde{G}^l$, $l = 1.....,r$

where r is the number of rules, and $\tilde{X}_1....,\tilde{X}_p$ and $\tilde{G}$ are type-2 fuzzy membership functions. A type-2 fuzzy set $\tilde{A}$, is characterized by the membership function:

$$\tilde{A} = \{((x,u), \mu_A(x,u)) \mid \forall x \in X, \forall u \in J_x \subseteq [0,1]\}$$

in which $0 \le \mu_{\tilde{A}}(x,u) \le 1$ for $x \in X$

1.5 Membership Functions

In fuzzy logic, the membership of every object in a specific set is determined by a matter of degree referred to as “degree of membership” which is defined via a Membership Function (MF). While in type-1 fuzzy sets, the degree of membership is specified by a crisp number belonging to the interval [0, 1]. In type-2 fuzzy sets, the degree of membership is in itself fuzzy and is represented by what is usually referred to as a secondary membership function. If the secondary membership function is at its maximum of 1 at every point, we speak of an interval type-2 set. Thus type-2 fuzzy sets include a third dimension and footprint of uncertainty as shown in Figure (6b) and Figure (6c) which gives them extra degrees of freedom to handle the faced uncertainties. A visual example of the three types of fuzzy sets is given in Figure (6).

In Figure (6), the same input p is applied to the three different types of fuzzy sets (type-1 fuzzy set in Figure (6a), interval type-2 fuzzy set in Figure (6b) and general type-2 fuzzy set in Figure (6c), resulting in a degree of membership which is specific to the type of fuzzy set. The amount of uncertainty (and the distribution) that is associated with the degree is shown in color in Figure(1) and is explained in Figure (7). It shows the secondary Membership Functions (MFs) (third dimension) of the type-1 fuzzy set (Figure (7a)), the interval type-2 fuzzy set (Figure (2b)) and the general type-2 fuzzy set (Figure (7c)) as induced by the same input p as shown in Figure (6). It should be noted that Figure (7) is visualizing the y-z plane.

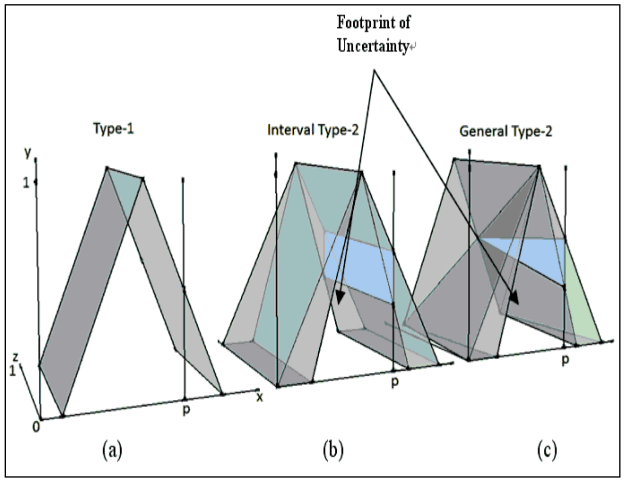

Figure 0.6: Types of fuzzy sets. The same input p is applied to each fuzzy set. (a) Type-1 fuzzy set. (b) Interval type-2 fuzzy set. (c) General type-2 fuzzy set.

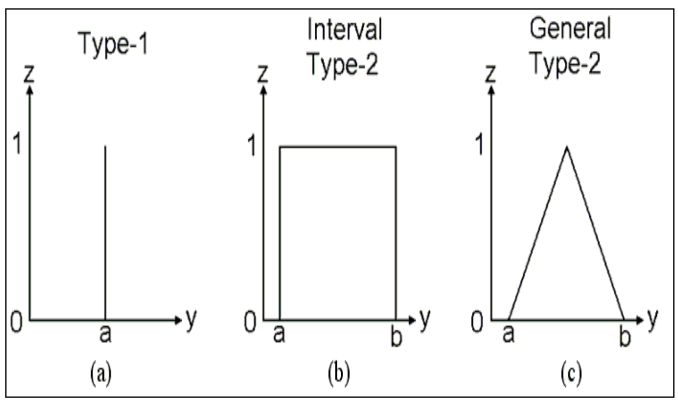

Figure 0.7: Secondary membership functions (third dimensions) induced by an input p for (a) Type-1 fuzzy set. (b) Interval Type-2 fuzzy, and (c) General type-2 sets.

Compared to type-1, type-2 FLCs are better at eliminating persistent oscillations in the system response. The reason for this is that a type-2 FLC has a very smooth control structure than type-1 FLC, particularly in and around the origin. Therefore, small variations around the steady state will not result in the change in the control signal and thereby resulting in fewer oscillations. A type-2 FLC has superior ability to handle uncertainty, so it generally performs well in practical applications. Despite of the various advantages offered by type-2 FLCs they have a drawback of higher computational cost [17], but this problem has become affordable with cheap computers involving high speed computations.

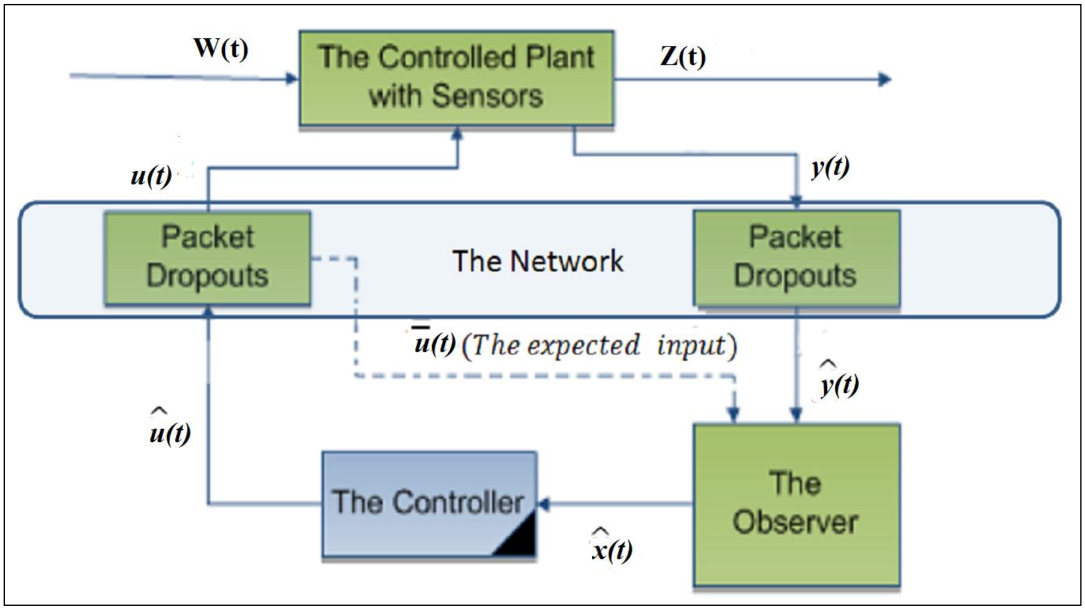

Figure 0.8: Block Diagram of the system

Figure 8 depicts the block diagram of a networked control system with data packet dropouts and the controller which will be designed. The controller is Type-2 FLC which is combined with an observer. The observer based Type -2 Fuzzy Logic Controller will be designed which is used to deal with the uncertainty in the system. The results of the Type-2 FLC will then be compared with that of the Type-1 FLC to show the effectiveness of the control technique.

1.6 Thesis Objectives

The main objectives of the thesis are to

- Developing Fuzzy type-2 observer based Control Technique for Networked Control Systems.
- Test the performance of the developed theory with simulations.
- Compare the results of type-2 FLC with Type-1 FLC.

1.7 Problem Statement

1.7.1 Plant Model

In this thesis, we consider a nonlinear networked control system as shown in Figure 3.1. In this system, we assume that the system is clock driven, takes samples periodically with a sampling period *h*, and sends the data to the controller through the network. The controller and actuator are event driven. In Figure 3.1, τ_{sc} represents the delay of data transmitted from the sensor to the controller and τ_{ca} represents the delay of the data transmitted from the controller to the actuator through the network. The plant can be described by,

$$\dot{x}(t) = Ax(t) + A_d x(t - \tau(t)) + Bu(t) \qquad (1.1)$$

where $x(t) \in \Re^n$ is the state vector , $u(t) \in \Re^m$ is the control input that is applied by the actuator. A_d is the constant real matrix that represents the delayed state matrix. $\tau(t)$ is the network transmission delay of the state. The system feedback control can be expressed as

$$u(t) = Gx(t)$$

Based on the above equations interval type-2 TS fuzzy model is designed for the state feedback and output feedback control of the networked control system.

1.7.2 Thesis Organization

This thesis contains several chapters, the first of which is the introduction. Chapter 2 shows the previous work on NCSs plants subject to estimation and various control theory that were developed. Chapter 3 contains the state feedback control design based on the Interval Type-2 TS fuzzy model is shown. Chapter 4 is focused on the design of an output feedback controller based on the Interval Type-2 TS fuzzy model is shown. In chapter 5 conclusions will be drawn and directions for future research will be presented.

Chapter 2

LITERATURE REVIEW

L. A. Zadeh [16] introduced the concept of type-2 fuzzy sets in the year 1975. Since then it has been used in various control problems for controlling different processes. Dongrui Wu et al [18] presented a simplified type-2 controller for real-time control. The basic idea was to replace some important type-1 fuzzy sets by type-2 sets, thereby solving the problem of system uncertainty. Experiments are conducted based on coupled tank liquid level control system to prove the robustness of the new method when compared to the conventional case. Roberto Sepulveda et al [19] presented a study that deals with the type 2 fuzzy sets used in fuzzy systems that can easily deal with the problem of uncertainty and also provides with more parameters and thereby we have degrees of freedom. The control systems are designed using type-2 fuzzy logic so as to minimize the effects of uncertainty produced by the noise and the process elements. Experiments are conducted in two classes, in the first class comparative results are shown for the type-1 and type-2 systems for a non-linear feedback control system, with and without considering uncertainty. For the second class, non-linear identification problem is presented for time-series prediction.

Galluzzo et al [20, 21] proposed the application of a type-2 FLC to a nonlinear system that exhibits bifurcations. A type-2 fuzzy logic controller is tested by simulation on a bioreactor system that can be assessed as a trans-critical bifurcation. The application of type-2 controller can be analyzed using a fermentation reactor. Two different type-2 controllers are compared. One that is already present in the literature and the second one which has been presented by the authors. The results of type-2 are then compared with the type-1 FLC and a basic PID controller. The type-2 FLC is found to give better control performance than compared to the other controllers. Results show the validity of the proposed controller in preventing the system from reaching bifurcation.

Observer based robust adaptive interval type-2 fuzzy tracking controller for multivariable nonlinear systems was proposed by Tsung Chih Lin et al [22]. It presents a new observer based indirect adaptive interval type-2 controller for nonlinear MIMO systems involving external disturbances and rule uncertainties. A fuzzy logic controller equipped with training algorithm based on universal approximation theorem is proposed. In [23], an adaptive interval type-2 fuzzy sliding mode controller for a class of unknown nonlinear discrete-time systems with training data corrupted by noise or rule uncertainties involving external disturbances. Adaptive interval type-2 fuzzy control scheme and sliding mode control (SMC) approach are incorporated to implement the main objective of controlling the plant to track a reference trajectory and prevent big chattering of the control effort.

The effect of network induced variable time delays in Networked Control Systems with the framework of type-1 and type-2 fuzzy logic is discussed in [24]. In fuzzy type-2 sets the uncertainty is represented as an extra dimension. Uncertainties such as variable time delays and packet dropouts must be covered by the control strategy design of the Networked Control Systems. Type-2 fuzzy sets present new framework of FLS and show promising results in dealing with the uncertainties. In [25], the wireless network effect on PI controller and type-2 fuzzy logic controller are studied. The network disadvantages are treated as uncertainty and they are reduced using type-2 FLC. The results are compared with PI controller.

Oscar Castillo et al [26] designed a trajectory tracking controller for a dynamic model of unicycle mobile robot. The controller is designed by integrating a kinematic and torque controller based on type-2 fuzzy logic theory. The design of the type-2 FLC is tested on a perturbed autonomous wheeled mobile robot. The application of Ant Colony Optimization (ACO) and Particle Swarm Optimization (PSO) on the optimization of the membership function parameters of a fuzzy logic controller (FLC) are discussed for an autonomous wheeled mobile robot [15, 27]. The results are compared with the results of genetic algorithm.

Abbadi A. et al [28] proposed a type-2 FLC that has the capability to improve the transient stability and reach voltage regulation concurrently for multi machine power systems. The design of the controller is based on the Direct Feedback Linearization (DFL) technique. The DFL compensated system model is transformed into an equivalent type-1 fuzzy model using linearly independent functions. The controller is applied to two-generator infinite bus power system.

Performance evaluation of interval type-2 FLC is carried out in [29]. A fuzzy logic type-2 controller is developed based on the Genetic Algorithms. Then it is compared with three Genetic Algorithm evolved type-1 FLCs that has different parameters. The test platform is a non-linear second order liquid level process. The main aim is to study the amount by which the extra degrees of freedom provided by type-2 FLC are able to improve the control performance. The model chosen is a coupled-tank liquid-level control system.

Mohammed Y. Hassan et al [30] proposed an approach to control Mean Arterial Pressure by controlling drug infusion using Interval Type-2 Fuzzy Logic Control. A number of values of uniform random noise were imposed to the system representing uncertainty and un-modeled dynamics that may appear in the model to test the controller robustness.

Ahmad H. El Khateb et al [31] proposed a concept of using a type-2 fuzzy logic controller (FLC) as a maximum power point tracker (MPPT), which can handle the uncertainties of the rules under high variations in weather conditions. The MPPT uses single-ended primary-inductor (SEPIC) converter. The new controller improves maximum power tracker search method. An accurate and fast converging to maximum power point is offered by type-2 fuzzy tracker during both steady-state and varying weather conditions compared to conventional fuzzy MPPT methods. Navigation of Autonomous Guided Vehicles is a very difficult task. In dynamic circumstances, traditional fuzzy controller using simple type-1 fuzzy sets may not be robust enough to overcome uncertainties. Therefore, there is a need for an interval type-2 fuzzy wall-following controller (IT2FWFC) to improve the resilience to inaccuracies that can hinder the normal operation of an AGV. The first part of the proposed controller is made up of type-2 fuzzy sets and its second part is formed from fuzzy singletons [32].

The application of the direct Lyapunov method to the stability analysis of systems controlled by type-2 fuzzy logic controllers (FLC) is presented in [33]. The method is applied to the stability analysis of a bioreactor and of a CSTR controlled by type-2 FLCs. It is usually applied to systems described by state equations and controlled by fuzzy controllers using state variables as inputs but has been extended to controllers that have the error and the integral of error of the controlled variable as inputs. Li Zhang et al [34] proposed a delayed state variable method for NCS upon which a LQR controller is designed. The online estimation of delays is carried out. A fuzzy logic with LQR controller is implemented because of the difficulty in implementing LQR in NCS with time-varying delays. Takagi–Sugeno (T–S) fuzzy model is used to calculate the gain (L) of the LQR controller online.

Song Shyong Chen et al [35] discussed the design of a robust static output feedback controller for a nonlinear network based controller for T-S fuzzy model. Effects of network induced delays and packet dropouts are also studied. The basic idea is to design a feedback gain for each local model and then to construct a global controller from these local gains so that the global stability of the overall fuzzy system can be guaranteed. An alternative approach of conducting stability analysis and control design by using the matrix spectral norm is also considered. Suk Lee et al [36] implemented a Networked Control System for motor speed control on a Profibus-DP network. The performance of the fuzzy logic Controller is compared with that of the conventional PID controller. A Remote Fuzzy Logic Controller is implemented to compensate the network-induced delay for a Single Input Single Output (SISO) Plant. In [37], a NCS for servo motor control is implemented on a Profibus-DP network. The FLC’s performance is compared with a conventional PID control.

Sharmila B. and Devarajan N. [38] proposed a remote DC motor actuation control with NCS. Fuzzy logic Controller methodology in the networked controlled DC motor control is proposed and the results are compared with Ziegler-Nichols tuned PID Controller and Fuzzy Modulated PID controller. In [39], a case study is presented. A project is designed with 3 sensors, 2 actuators, and an observer program for process control to implement a real-time control system. El Ougli A. et al [40] proposed a robust adaptive fuzzy controller for a class of nonlinear system with unknown dynamics. The method is based on type-2 fuzzy logic system to approximate unknown non-linear function. The main advantage of the proposed adaptive fuzzy controller is that it does not need any knowledge about the nonlinear term. In [41], a novel control method which addresses the varying time delay problem effectively is introduced. This novel method suggests an online adaptive fuzzy logic controller which have been controlled and adapted through the neural network. This method takes the advantage of the genetic algorithm to optimize the membership functions for its fuzzy logic controller. This designed controller is applied to an AC 400 W servo motor as a remote plant in order to control the position via Ethernet.

Chwan-Lu Tseng et al [42] proposed a study that discusses an interval type-2 controller design method for a class of nonlinear singular networked control systems encountering data-transmission delay and packet loss problems. This study assesses the stability analysis and design of the system controllers. First, the singular networked control systems are modeled as interval type-2 T-S fuzzy systems. The concept of parallel distributed compensation is then employed to design corresponding interval type-2 T-S fuzzy controllers. This study considers a class of nonlinear singular networked control systems where transmission delay and packet loss issues are converted into input time delays. Here state feedback controller is designed using FLC type-2.

Chapter 3

DESIGN OF TYPE 2 FLC BASED STATE FEEDBACK CONTROLLER FOR NCS

3.1 Introduction:

In this chapter, we design a state feedback controller for a NNCS on the existing packet loss and delays. The type of NNCS will be a state feedback based controller. The analysis in this chapter is a reproduction for the work of Chwan-Lu Tseng et al [42] in addition to a modification of the Linear Matrix Inequality (LMI). An interval type-2 controller for a class of nonlinear singular networked control systems facing data transmission delay and packet loss problems is designed. Here the transmission delay and packet loss issues are converted into input time delays. The singular networked control systems are modeled as interval type-2 T-S fuzzy systems. The concept of parallel distributed compensation is then employed to design corresponding type-2 T-S fuzzy controllers. For checking the stability of the system, the stability conditions are identified using a specific Lyapunov function. The linear matrix inequalities are derived from the stability conditions. Then the controller gain is calculated by solving the linear matrix inequalities. Finding the unknown parameters increases the amount of coupling between the equations. As a consequence, this in turn will increase the number of unknown parameters. The LMI was formulated using only two terms in the Lyapunov krasovskii functional. So in this chapter, a NNCS controller is designed based on the state feedback method through LMI approach. The LMI is formulated by taking up to five terms in the Lyapunov krasovskii functional. The efficiency of the newly formed controller is verified with the help of simulations. The design of the controller is explained in detail.

3.2 Problem Formulation:

The structure of a typical networked control system is shown in Figure 3.1. The controlled plant is a nonlinear system. Similar to [42], it has been assumed that the sensor is clock driven, takes samples periodically with a sampling period *h*, and sends the data to the controller through the network. The controller and actuator are event driven. In the Figure 3.1, τ_{sc} represents the delay of data transmitted from the sensor to the controller through the network, and τ_{ca} represents the delay of data transmitted from the controller to the actuator through the network. Assume that the plant in Figure 3.1 can be described by,

$$\dot{x}(t) = Ax(t) + A_d x(t - \tau(t)) + Bu(t) \tag{3.1}$$

Where $x(t) \in \Re^n$ is the state vector, $A_d \in \Re^n$ is the constant real matrix that represents the delayed state matrix. $\tau(t)$ is the network transmission delay of state. The system feedback control can be expressed as,

$$u(t) = Kx(t) \tag{3.2}$$

To accommodate the construction of a networked control system model, the following assumptions are made:

1. Assume that the packets remain ordered during transmission.
2. The time allocated for calculating the control signals is ignored.

3. If no data is transmitted from the sensor to the control or from the controller to the actuator within the sampling period *h*, then the packet is assuemed lost.
4. If a packet is lost, the previous sample is used as the control input signal.
5. When the actuator receives conrol signals from the controller, it immediately executes the corresponding instruction.
6. The transmission delay of the entire closed-loop network varies according to time. We assume that $\tau_k = \tau_{sc}^k + \tau_{ca}^k$

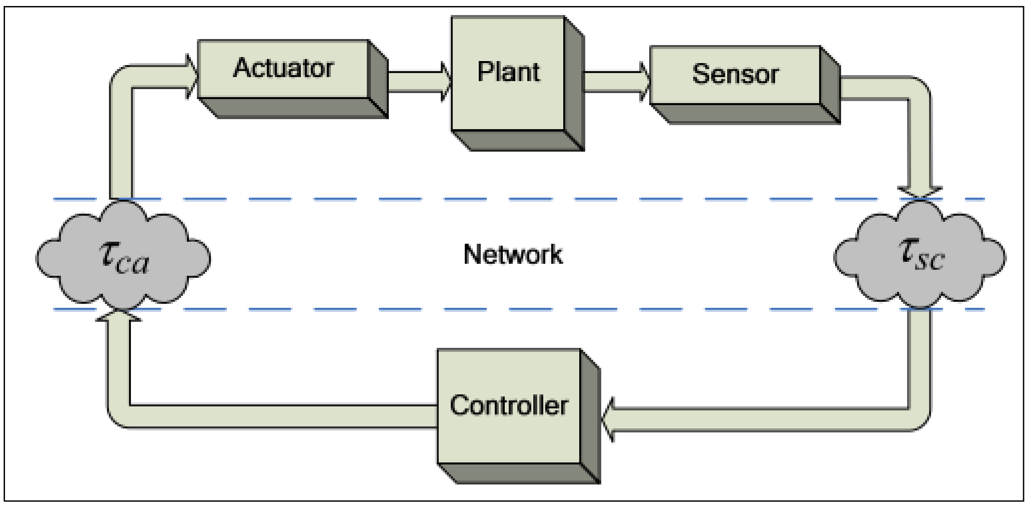

Figure 3.1: Networked Control system structure [42]

The variable N_k is defined as a positive integer that represents the number of continuous packets lost after the k^{th} sampling period. Let us consider that at the sampling time t_{k+1}, two continuous packet losses occurred between sensor and controller. Therefore, we set $N_{k+1} = 2$. Considering simultaneous transmission delays and packet losses, if time *t* is the sampling time t_k, the control input signal can be expressed as,

$$u(t) = u(t_k) = Kx(t_k), t_k + \tau_k \le t \le t_{k+1} + N_{k+1}h + \tau_{(k+1)+2}$$

At sampling time t_{k+1}, $N_{k+1} = N$, continuous packet losses occured between the sensor and controller and between the controller and actuator. The control input signal can be expressed as,

$$u(t) = u(t_k) = Kx(t_k), t_k + \tau_k \leq t \leq t_{k+1} + Nh + \tau_{(k+1)+N}$$

Without loss of generality, there exists a positive variable ω_k, such that $t_k + \tau_k + \omega_k = t$; thus, we get $t_k = t - (\tau_k + \omega_k)$. Let $\phi(t) = \tau_k + \omega_k$, the control input can be written as,

$$u(t) = u(t - \phi(t)) = Kx(t - \phi(t))$$

Since, $\tau_k + \omega_k = t - t_k$ and $t < t_{k+1} + Nh + \tau_{(k+1)+N}$, we can derive,

$$\tau_k + \omega_k < t_{k+1} + Nh + \tau_{(k+1)+N} - t_k = (N+1)h + \tau_{(k+1)+N} \leq (N+2)h$$

Based on this, we can conclude that $\phi(t) \in [0, (N+2)h]$. Therefore the dynamic equation of the controlled object can be written as in Eq. (3.3). For simplifying the stability analysis of the NCS, we assume that th network transmission delay of the state $\tau(t) = \phi(t)$.

$$\dot{x}(t) = Ax(t) + A_d x(t - \phi(t)) + Bu(t)$$

$$u(t) = Kx(t - \phi(t)), \phi(t) \in [0, (L+2)h] \tag{3.3}$$

And the output of the system is given as

$$y(t) = Cx(t) \tag{3.4}$$

The above equation describes a linear networked control system. Using this methodology, we can understandably use the interval type-2 T-S fuzzy model to describe a class of nonlinear systems with the linear subsytem as shown in Eq. (3.3) and design a feedback controller.

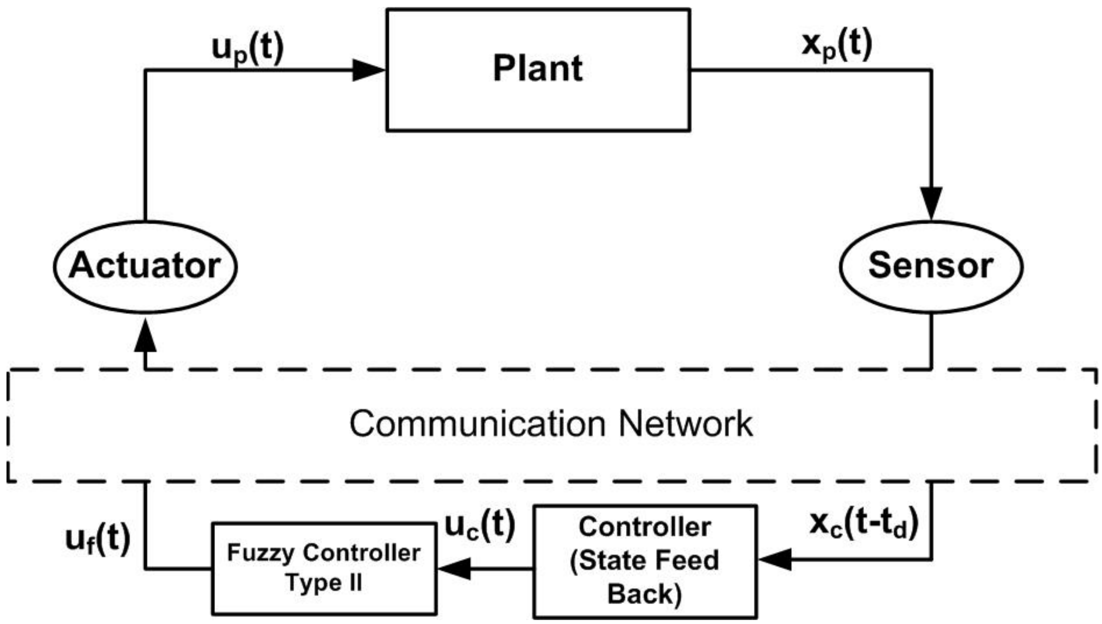

Figure 3.2 Block Diagram of a State Feedback Controller

3.3 State Feedback Controller Design

There is a lot of literature that introduces the concept of interval type-2 T-S fuzzy control systems. The main concept of T-S fuzzy control systems makes use of IF-THEN rules, but the fuzzy set is an interval fuzzy set. Let $\tilde{M}$ be the interval type-2 T-S fuzzy set. The upper and lower interval type-2 T-S fuzzy membership functions are represented as $\overline{\mu}_{\tilde{M}}(x)$ and $\underline{\mu}_{\tilde{M}}(x)$ and $0 < \overline{\mu}_{\tilde{M}}(x) < \underline{\mu}_{\tilde{M}}(x) \leq 1$. The i^{th} model rule is expressed as,

Model rule i

IF $z_1(t)$ is M_1^i and …. And $z_p(t)$ is M_p^i

THEN $\dot{x}(t) = A_i x(t) + B_i u(t), i = 1..., r$

Here r is the number of IF-THEN rules. $z_1(t), z_2(t),..., z_p(t)$ are linguistic variables. $\tilde{M}_k^i$ $(k = 1,2,...p, i = 1,2,...r)$ are interval type-2 fuzzy sets. $x(t) \in \Re^n$ is the state vector of th system. $u(t) \in \Re^m$ is the input vector of the system. A is the state matrix, B is the input matrix of the system. Let $z(t) = [z_1(t) \quad z_2(t) \quad ... \quad z_p(t)]$. Using the product operations, the upper membership grade $\omega_i^U(z(t))$ and lower membership grade $\omega_i^L(z(t))$ are defined as

$$\omega_i^U(z(t)) = \prod_{j=1}^{p} \overline{\mu}_{\tilde{M}_j^i}(z_j(t)) \geq 0, \quad \omega_i^L(z(t)) = \prod_{j=1}^{p} \underline{\mu}_{\tilde{M}_j^i}(z_j(t)) \geq 0,$$

where,

$$\overline{\mu}_{\tilde{M}_j^i}(z_j(t)) > \underline{\mu}_{\tilde{M}_j^i}(z_j(t)), \quad \omega_i^U(z(t)) \geq \omega_i^L(z(t)).$$

The interval type-2 system can be modeled by the following system,

$$\dot{x}(t) = \sum_{i=1}^{r} \tilde{h}_i(z(t))\{A_i x(t) + B_i u(t)\} \tag{3.5}$$

Where

$$\tilde{h}_i(z(t)) = \frac{\tilde{\omega}_i(z(t))}{\sum_{i=1}^{r} \tilde{\omega}_i(z(t))} \text{ and } \sum_{i=1}^{r} \tilde{h}_i(z(t)) = 1$$

$$\tilde{\omega}_i(z(t)) = \omega_i^U(z(t))\overline{\rho}_i(z(t)) + \omega_i^L(z(t))\underline{\rho}_i(z(t))$$

$$\overline{\rho}_i(z(t)) \in [0,1], \ \underline{\rho}_i(z(t)) \in [0,1], \ \overline{\rho}_i(z(t)) + \underline{\rho}_i(z(t)) = 1$$

The interval type-2 T-S fuzzy controller design is based on the concept of PDC. Suppose that the interval type-2 T-S fuzzy controller consists of r control rules. The i^{th} control rule is given as,

Control Rule i

IF $z_1(t)$ is M_1^i and …. And $z_p(t)$ is M_p^i

THEN $u(t) = K_i x(t), i = 1..., r$

where $G_i \in \Re^{m \times n}$ is the feedback control gain matrix. The output of the fuzzy controller can be derived as,

$$u(t) = \sum_{i=1}^{r} \tilde{h}_i(z(t)) K_j x(t) \tag{3.6}$$

For simplicity in calculations, $\tilde{h}_i(z(t))$ is simplified to $\tilde{h}_i$. Now substituting Eq. (3.6) in Eq. (3.5), the complete closed-loop system is formulated as,

$$\dot{x}(t) = \sum_{i=1}^{r} \sum_{j=1}^{r} \tilde{h}_i \tilde{h}_j \{A_i x(t) + B_i K_j x(t)\} \tag{3.7}$$

Suppose the considered nonlinear networked control system is modeled as interval type-2 T-S fuzzy systems that comprise of r rules. The i^{th} model rule is expressed as:

Model Rule i

IF $z_1(t)$ is M_1^i and …. And $z_p(t)$ is M_p^i

THEN $\dot{x}(t) = A_i x(t) + A_{di} x(t - \phi(t)) + B_i u(t), i = 1..., r$

Control rule i

IF $z_1(t)$ is M_1^i and …. And $z_p(t)$ is M_p^i

THEN $u(t) = K_i x(t-\phi(t)), i = 1..., r$

Similar to Eq.(3.7), the networked control system can be modeled as,

$$\dot{x}(t) = \sum_{i=1}^{r}\sum_{j=1}^{r}\tilde{h}_i(z(t))\{A_i x(t) + A_{di}x(t-\phi(t)) + B_i u(t)\}$$

$$u(t) = \sum_{i=1}^{r}\tilde{h}_i(z(t))K_i x(t-\phi(t)), \phi(t) \in [0,(L+2)h] \tag{3.8}$$

In the above equations, $\phi(t)$ is the transmission delay of the networked control system, and L is the number of continuous packets lost. After substituing Eq. (3.8) in Eq. (3.7), the entire closed-loop networked control system is obtained as

$$\dot{x}(t) = \sum_{i=1}^{r}\tilde{h}_i\tilde{h}_j\{A_i x(t) + A_{di}x(t-\phi(t)) + B_i K_j x(t-\phi(t))\} \tag{3.9}$$

Based on Eq.(3.9) the results are being obtained.

Note that,

$$A = \sum_{i=1}^{r} h_i A_i \ , \ A_{di} = \sum_{i=1}^{r} h_i A_{di} \ , \ A_{\phi} = \sum_{i=1}^{r}\sum_{j=1}^{r} h_i h_j B_i K_j$$

Then the closed loop system (3.9) can be defined as,

$$\dot{x}(t) = Ax(t) + A_{di}x(t-\phi(t)) + A_{\phi}x(t-\phi(t)) \tag{3.10}$$

$$y = Cx(t)$$

The design of Lyapunov Krasovskii Functional is explained in the next section. In [43], the state feedback controller is designed for a type-2 fuzzy controller. The author considered only up to two terms for the Lyapunov Krasovskii theory. We have extended this to five terms. The detailed explanation is shown in next section.

3.4 Main Results:

Theorem 1*:* *For any given scalars* $\phi_1 > 0, \phi_2 > 0, \mu_1 > 0, \mu_2 > 0, \tau_1 > 0, \tau_2 > 0$, and matrix K_j, *closed loop system is asymptotically stable if there exists positive matrices* P, Q_1, Q_2, Z_1, Z_2 *and a matrix G with appropriate dimensions, such that* $\Lambda < 0$

$$\Lambda = \begin{bmatrix} \Lambda_{11} & \Lambda_{12} & \Lambda_{13} & 0 & \Lambda_{15} \\ * & \Lambda_{22} & \Lambda_{23} & \Lambda_{24} & \Lambda_{25} \\ * & * & \Lambda_{33} & 0 & 0 \\ * & * & * & \Lambda_{44} & 0 \\ * & * & * & * & \Lambda_{55} \end{bmatrix} \tag{3.11}$$

$$\Lambda_{11} = Q_1 + Q_2 - Z_1 + A^T G + G^T A$$

$$\Lambda_{12} = A_\phi{}^T G + A_{di}{}^T G + \tau_1 A^T G$$

$$\Lambda_{13} = Z_1$$

$$\Lambda_{15} = P - G^T + \tau_2 A^T G$$

$$\Lambda_{22} = -2Z_2 + \tau_1 A_{di}{}^T G + \tau_1 A_\phi{}^T G + \tau_1 G^T A_{di} + \tau_1 G^T A_\phi$$

$$\Lambda_{23} = Z_2{}^T$$

$$\Lambda_{24} = Z_2$$

$$\Lambda_{25} = -\tau_1 G + \tau_2 A_{di}^T G + \tau_2 A_\phi^T G$$

$$\Lambda_{33} = -(1 - \mu_1) Q_1 - Z_1 - Z_2$$

$$\Lambda_{44} = -(1-\mu_2)Q_2 - Z_2$$

$$\Lambda_{55} = \phi_1{}^2 Z_1 + \phi_r{}^2 Z_2 - \tau_2 G - \tau_2 G^T$$

Proof: The closed loop system is given by,

$$\dot{x}(t) = Ax(t) + A_{di}x(t-\phi(t)) + A_{\phi}x(t-\phi(t))$$

Let us assume that the transmission delay in the networked control system is given by $\phi(t)$. Let the transmission delay has upper and lower bounds and the are represented as,

$$\phi_1 \le \phi(t) \le \phi_2$$

We also can assume $\dot{\phi}_1 < \mu_1 < 1$ and $\dot{\phi}_2 < \mu_2 < 1$

The Lyapunov-krasovskii functional is given by,

$$V(x_t) = V_1(t) + V_2(t) + V_3(t) + V_4(t) + V_5(t)$$

$$V_1(t) = x^T(t)Px(t)$$

$$V_2(t) = \int_{t-\phi_1}^{t} x^T(s)Q_1x(s)ds$$

$$V_3(t) = \int_{t-\phi_2}^{t} x^T(s)Q_2x(s)ds$$

$$V_4(t) = \phi_1 \int_{-\phi_1}^{0}\int_{t+\theta}^{t} \dot{x}^T(s)Z_1\dot{x}(s)dsd\theta$$

$$V_5(t) = \phi_r \int_{-\phi_r}^{0} \int_{t+\theta}^{t} \dot{x}^T(s) Z_2 \dot{x}(s) ds d\theta$$

with $\phi_r = \phi_2 - \phi_1$.

Taking the time derivative of V(x) we get,

$$\dot{V}_1(t) = x^T(t) P \dot{x}(t) + \dot{x}^T(t) P x(t)$$

$$\dot{V}_2(t) = x^T(t) Q_1 x(t) - (1 - \dot{\phi}_1) x^T(t - \phi_1) Q_1 x(t - \phi_1)$$

$$\dot{V}_3(t) = x^T(t) Q_2 x(t) - (1 - \dot{\phi}_2) x^T(t - \phi_2) Q_2 x(t - \phi_2)$$

$$\dot{V}_4(t) = \phi_1^2 \dot{x}^T(t) Z_1 \dot{x}(t) - \phi_1 \int_{t-\phi_1}^{t} \dot{x}^T(s) Z_1 \dot{x}(s) ds$$

Now consider,

$$-\phi_1 \int_{t-\phi_1}^{t} \dot{x}^T(s) Z_1 \dot{x}(s) ds \leq \begin{bmatrix} x(t) \\ x(t-\phi_1) \end{bmatrix}^T \begin{bmatrix} -Z_1 & Z_1 \\ * & -Z_1 \end{bmatrix} \begin{bmatrix} x(t) \\ x(t-\phi_1) \end{bmatrix}$$

$$= -x^T(t) Z_1 x(t) + x^T(t-\phi_1) Z_1^T x(t) + x^T(t) Z_1 x(t-\phi_1) - x^T(t-\phi_1) Z_1 x(t-\phi_1)$$

Now,

$$\dot{V}_4(t) = \phi_1^2 \dot{x}^T(t) Z_1 \dot{x}(t) - x^T(t) Z_1 x(t) + x^T(t-\phi_1) Z_1^T x(t) + x^T(t) Z_1 x(t-\phi_1) - x^T(t-\phi_1) Z_1 x(t-\phi_1)$$

$$\dot{V}_5(t) = \phi_r^2 \dot{x}^T(t) Z_2 \dot{x}(t) - \phi_r \int_{t-\phi_r}^{t} \dot{x}^T(s) Z_2 \dot{x}(s) ds$$

Consider,

$$-\phi_r\int_{t-\phi_r}^{t}\dot{x}^T(s)Z_2\dot{x}(s)ds \le -\phi_r\int_{t-\phi_2}^{t-\phi(t)}\dot{x}^T(s)Z_2\dot{x}(s)ds-\phi_r\int_{t-\phi(t)}^{t-\phi_1}\dot{x}^T(s)Z_2\dot{x}(s)ds$$

$$-\phi_r\int_{t-\phi_2}^{t-\phi(t)}\dot{x}^T(s)Z_2\dot{x}(s)ds \le \begin{bmatrix} x(t-\phi(t)) \\ x(t-\phi_2) \end{bmatrix}^T \begin{bmatrix} -Z_2 & Z_2 \\ * & -Z_2 \end{bmatrix} \begin{bmatrix} x(t-\phi(t)) \\ x(t-\phi_2) \end{bmatrix}$$

$$\le -x^T(t-\phi(t))Z_2x(t-\phi(t))+x^T(t-\phi_2)Z_2^Tx(t-\phi(t))+x^T(t-\phi(t))Z_2x(t-\phi_2)$$
$$-x^T(t-\phi_2)Z_2x(t-\phi_2)$$

$$-\phi_r\int_{t-\phi(t)}^{t-\phi_1}\dot{x}^T(s)Z_2\dot{x}(s)ds \le \begin{bmatrix} x(t-\phi_1) \\ x(t-\phi(t)) \end{bmatrix}^T \begin{bmatrix} -Z_2 & Z_2 \\ * & -Z_2 \end{bmatrix} \begin{bmatrix} x(t-\phi_1) \\ x(t-\phi(t)) \end{bmatrix}$$

$$\le -x^T(t-\phi_1)Z_2x(t-\phi_1)+x^T(t-\phi(t))Z_2^Tx(t-\phi_1)+x^T(t-\phi_1)Z_2x(t-\phi(t))$$
$$-x^T(t-\phi(t))Z_2x(t-\phi(t))$$

$$\dot{V}_5(t)=\phi_r^2\dot{x}^T(t)Z_2\dot{x}(t)-x^T(t-\phi(t))Z_2x(t-\phi(t))+x^T(t-\phi_2)Z_2^Tx(t-\phi(t)))$$

$$+x^T(t-\phi(t))Z_2x(t-\phi_2)-x^T(t-\phi_2)Z_2x(t-\phi_2)-x^T(t-\phi_1)Z_2x(t-\phi_1)$$

$$+x^T(t-\phi(t))Z_2^Tx(t-\phi_1)+x^T(t-\phi_1)Z_2x(t-\phi(t))-x^T(t-\phi(t))Z_2x(t-\phi(t)$$

Now,

$$\dot{V}(t)=\dot{V}_1(t)+\dot{V}_2(t)+\dot{V}_3(t)+\dot{V}_4(t)+\dot{V}_5(t) \tag{3.12}$$

$$\dot{V}(t)=x^T(t)P\dot{x}(t)+\dot{x}^T(t)Px(t)+x^T(t)Q_1x(t)-(1-\dot{\phi}_1)x^T(t-\phi_1)Q_1x(t-\phi_1)$$

$$+x^T(t)Q_2x(t)-(1-\dot{\phi}_2)x^T(t-\phi_2)Q_2x(t-\phi_2)+\phi_1^2\dot{x}^T(t)Z_1\dot{x}(t)-x^T(t)Z_1x(t)+x^T(t-\phi_1)Z_1^Tx(t)$$

$$+x^T(t)Z_1x(t-\phi_1)-x^T(t-\phi_1)Z_1x(t-\phi_1)+\phi_r^2\dot{x}^T(t)Z_2\dot{x}(t)-x^T(t-\phi(t))Z_2x(t-\phi(t))$$

$$+x^T(t-\phi_2)Z_2^T x(t-\phi(t))+x^T(t-\phi(t))Z_2 x(t-\phi_2)-x^T(t-\phi_2)Z_2 x(t-\phi_2)-x^T(t-\phi_1)Z_2 x(t-\phi_1)$$

$$+x^T(t-\phi(t))Z_2^T x(t-\phi_1)+x^T(t-\phi_1)Z_2 x(t-\phi(t))-x^T(t-\phi(t))Z_2 x(t-\phi(t)$$

A matrix G with appropriate dimensions can be constructed as shown in the following equation,

$$2(x^T(t)G^T+\tau_1 x^T(t-\phi(t))G^T+\tau_2\dot{x}(t)G^T)\times(-\dot{x}(t)+Ax(t)+A_\phi x(t-\phi(t))+A_{di}x(t-\phi(t)))=0 \tag{3.13}$$

Defining,

$$\xi(t)=[x^T(t) \quad x^T(t-\phi(t)) \quad x^T(t-\phi_1) \quad x^T(t-\phi_2) \quad \dot{x}^T(t)]^T$$

Then from (3.12) and (3.13), we have

$$\dot{V}(x_t)\le\xi^T(t)\Lambda\xi(t)$$

and Λ is defined in (3.11)

Thus, according to Lyapunov stability theory, there exist a scalar α such that, $\dot{V}x(t)<\alpha\|x_t\|$. We can conclude that the system Eq. (3.10) is asymptotically stable.

The objective now is to determine the gain matrices K_j, such that the feedback closed-loop system is asymptotically stable.

Since,

$$A_\phi{}^T G=(B_i K_j)^T G=K_j^T B_i^T G \tag{3.14}$$

In the above Eq. (3.14) there are two unknowns K_j and G, so Λ in (3.11) is bilinear. In the following theorem we try to linearize Λ, such that we will be able to find the controller gain K_i. In order to derive the gains we first introduce the following assumption and lemma.

Assumption 1: [6] *The matrix B is full column rank matrix, i.e.,* $rank(B) = m$ *and there exists two orthogonal matrices* $U \in \Re^{n\times n}$ and $V \in \Re^{m\times m}$*, such that*

$$S = UBV = \begin{bmatrix} U_1 \\ U_2 \end{bmatrix} BV = \begin{bmatrix} B_1 \\ 0 \end{bmatrix} \tag{3.15}$$

where, $U_1 \in \Re^{m\times n}$ *and* $U_2 \in \Re^{(n-m)\times n}$ *and* $B_1 = diag(b_1, b_2, ...b_m)$ *where* $b_i\,(i = 1,2,...,m)$*, are nonzero singular values of B.*

Lemma 1: [6] *For any matrix* $B \in \Re^{m\times n}$ *that is a full column rank matrix, if a matrix P is of the form*

$$P = U^T \begin{bmatrix} P_1 & 0 \\ 0 & P_2 \end{bmatrix} U = U_1^T P_1 U_1 + U_2^T P_2 U_2 \tag{3.16}$$

where $P_1 \in \Re^{m\times m} > 0$ *and* $P_2 \in \Re^{(n-m)\times(n-m)} > 0$, U_1 *and* U_2 *are defined in assumption 1, then there exists a non-singular matrix* $P_1 \in \Re^{m\times m} > 0$ *such that* $BP_1 = PB$*.*

By this Lemma, we can change the Eq. (3.14) so as to remove the bilinearity in the system and derive the controller gain K_i.

Theorem 2: *For any given scalars* $\phi_1 > 0$, $\phi_2 > 0$, $\mu_1 > 0$, $\mu_2 > 0$, $\tau_1 > 0$, $\tau_2 > 0$, closed *loop system is asymptotically stable if there exists matrices* $P > 0$, $Q_1 > 0$, $Q_2 > 0$, $Z_1 > 0$, $Z_2 > 0$, Y_i *and a matrix G with appropriate dimensions, such that* $\Lambda < 0$

$$\Lambda = \begin{bmatrix} \Lambda_{11} & \Lambda_{12} & \Lambda_{13} & 0 & \Lambda_{15} \\ * & \Lambda_{22} & \Lambda_{23} & \Lambda_{24} & \Lambda_{25} \\ * & * & \Lambda_{33} & 0 & 0 \\ * & * & * & \Lambda_{44} & 0 \\ * & * & * & * & \Lambda_{55} \end{bmatrix} \tag{3.14}$$

$$\Lambda_{11} = Q_1 + Q_2 - Z_1 + A_i^T G + G^T A_i$$

$$\Lambda_{12} = Y_i B_i^T + A_{di}^T G + \tau_1 A_i^T G$$

$$\Lambda_{13} = Z_1$$

$$\Lambda_{15} = P - G^T + \tau_2 A_i^T G$$

$$\Lambda_{22} = -2Z_2 + \tau_1 A_{di}^T G + \tau_1 G^T A_{di} + \tau_1 Y_i B_i^T + \tau_1 B_i Y_i^T$$

$$\Lambda_{23} = Z_2^T$$

$$\Lambda_{24} = Z_2$$

$$\Lambda_{25} = -\tau_1 G + \tau_2 A_{di}^T G + \tau_2 Y_i B_i^T$$

$$\Lambda_{33} = -(1-\mu_1)Q_1 - Z_1 - Z_2$$

$$\Lambda_{44} = -(1-\mu_2)Q_2 - Z_2$$

$$\Lambda_{55} = \phi_1^{\ 2} Z_1 + \phi_r^{\ 2} Z_2 - \tau_2 G - \tau_2 G^T$$

Proof: Under the conditions from Theorem 1 and Lemma 1 we can further simplify the LMI to calculate the feedback gains. Further simplifications can be done to the LMI as follows,

Based on the Lemma, we can simplify the LMI to calculate the gains,

$$\Lambda_{11} = Q_1 + Q_2 - Z_1 + A_i^{\ T} G + G^T A_i$$

$$\Lambda_{12} = K_j^{\ T} G_1 B_i^T + A_{di}^{\ T} G + \tau_1 A_i^{\ T} G$$

$$\Lambda_{13} = Z_1$$

$$\Lambda_{15} = P - G^T + \tau_2 A_i^{\ T} G$$

$$\Lambda_{22} = -2Z_2 + \tau_1 A_{di}^{\ T} G + \tau_1 G^T A_{di} + \tau_1 K_j^{\ T} G_1 B_i^T + \tau_1 B_i G_1^{\ T} K_j$$

$$\Lambda_{23} = Z_2^{\ T}$$

$$\Lambda_{24} = Z_2$$

$$\Lambda_{25} = -\tau_1 G + \tau_2 A_{di}^T G + \tau_2 (B_i K_j)^T G$$

$$\Lambda_{33} = -(1 - \mu_1) Q_1 - Z_1 - Z_2$$

$$\Lambda_{44} = -(1 - \mu_2) Q_2 - Z_2$$

$$\Lambda_{55} = \phi_1^{\ 2} Z_1 + \phi_r^{\ 2} Z_2 - \tau_2 G - \tau_2 G^T$$

Now using the Lemma, we can write $K_j^T G_1 = Y_i$ or $G_1^T K_j = Y_i^T$.

The formulated LMI is solved using the YALMIP toolbox in MATLAB and the gain is calculated accordingly.

If the linear matrix Inequality Eq.(3.14) is satisfied for every i and $\dot{V}(t)$ is negative definite, then the closed-loop networked control system in Eq.(3.9) is asympotically stable. The feedback control gain can be given as $K_j = Y_i^T G_1^{-T}$. This completes the proof.

In [43], a state feedback controller with Type-2 Fuzzy Logic Control is designed for Singular Networked Control Systems. The author considered only up to two terms for defining the Lyapunov Krasovskii functional for solving the Linear Matrix Inequality (LMI). We have taken the same concept of designing a state feedback controller for NCS. We have extended the concept and considered up to five terms in designing the Lyapunov Krasovskii functional to formualte the LMI.

3.5 Numerical Example:

Consider the nonlinear networked control system with three fuzzy rules and the following information:

$$A_1 = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 1 & 5 & 6 \end{bmatrix}, A_2 = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 1 & 2 & 6 \end{bmatrix}, A_3 = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 1 & 1 & 6 \end{bmatrix}$$

$$B_1 = \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix}, B_2 = \begin{bmatrix} 0 \\ 0 \\ 0.1 \end{bmatrix}, B_3 = \begin{bmatrix} 0 \\ 0.1 \\ 1 \end{bmatrix}$$

$$A_{d1} = A_{d2} = A_{d3} = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0.8 & 0 & 0 \end{bmatrix},\ C = \begin{bmatrix} 1 & 1 & 1 \end{bmatrix}$$

To perform the simulation, the sampling time is set to *h*=0.01s, and the initial condition is assumed to be $x_0 = \begin{bmatrix} 0.5 & -1 & 0.22 \end{bmatrix}'$. The network induced delays are defined by the equation as $\phi(t) = 1.2 + 0.8|\sin(t)|$. The constants are set as $\mu_1 = 0.2,\ \mu_2 = 0.3$, $\tau_1 = 0.02$, $\tau_2 = 0.03$.

Case 1: For $\phi_1 = 1.2$, $\phi_2 = 2$ we get a set of controller gains that can be calculated.

Based on the Theorem 3, the LMI is solved using the YALMIP toolbox in MATLAB and the feedback controller gains are calculated to be,

$$K_1 = \begin{bmatrix} 0.0070 & -0.0067 & -0.4109 \end{bmatrix}$$

$$K_2 = \begin{bmatrix} 0.2580 & 0.1323 & -2.4205 \end{bmatrix}$$

$$K_3 = \begin{bmatrix} -0.0118 & -0.0225 & -0.1852 \end{bmatrix}$$

The response of the states for the state feedback controller are shown in Figure 3.4. The networked induced delays are shown in Figure 3.3.

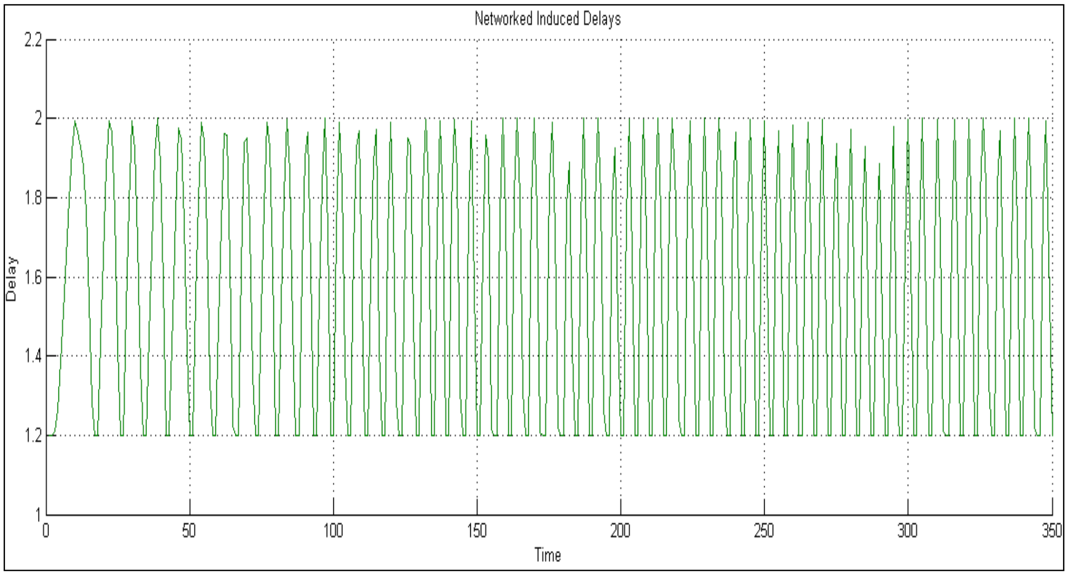

Figure 3.3: Network Induced Delays

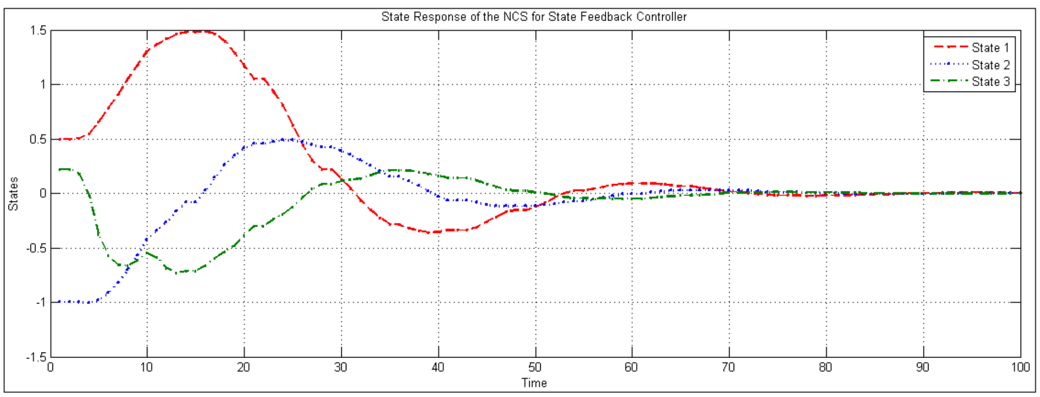

Figure 3.4: State Response to the State Feedback Controller

It can be inferred from the response that, the system response is much better in the delay range of $\phi_1 = 1.2$, $\phi_2 = 2$ ie., the settling time is around 80 sec which is supposed to be the best response for the given delay $\phi(t) = 1.2 + 0.8|\sin(t)|$.

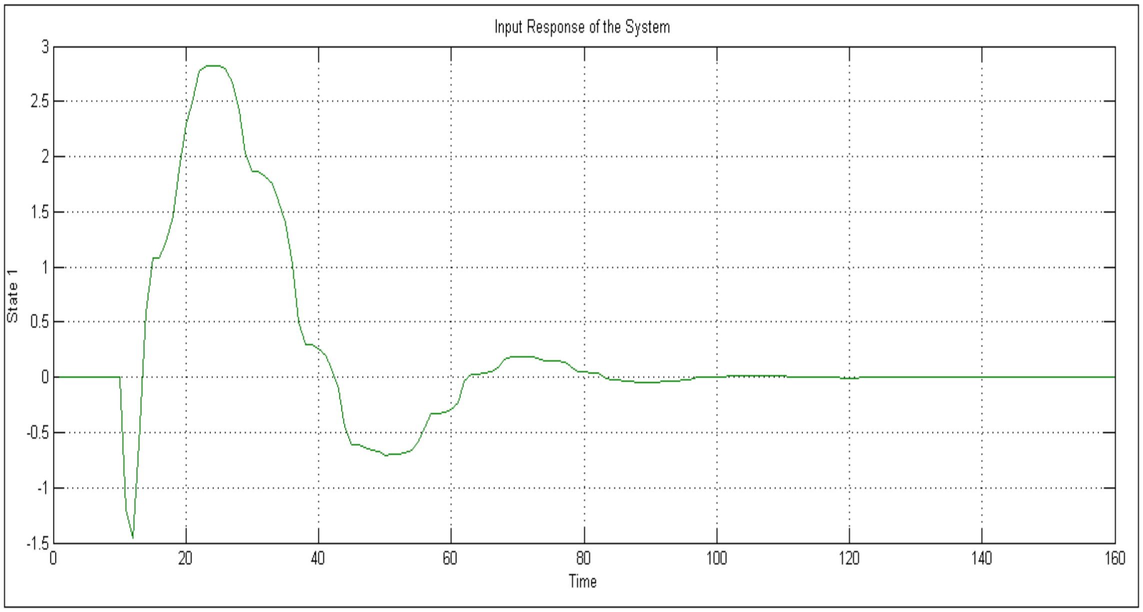

Figure 3.5: Control Input Response

Now, the results of the Type-2 Fuzzy Logic Controller are compared with that of the Type-1 Fuzzy Logic Controller. The results are as shown in Figures 3.6-3.8.

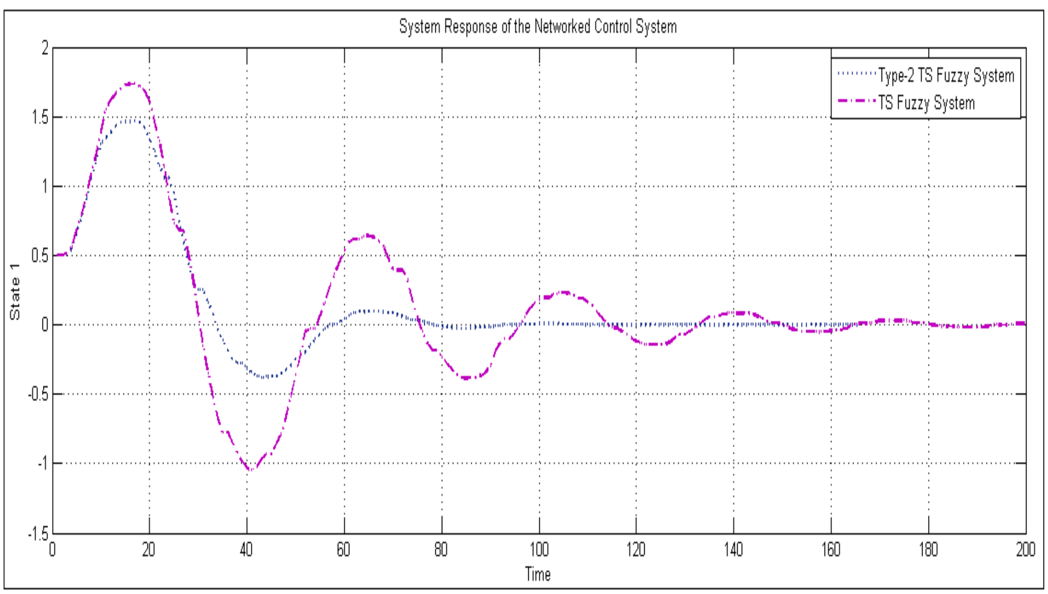

Figure 3.6: Type-2 TS Fuzzy System vs TS Fuzzy System

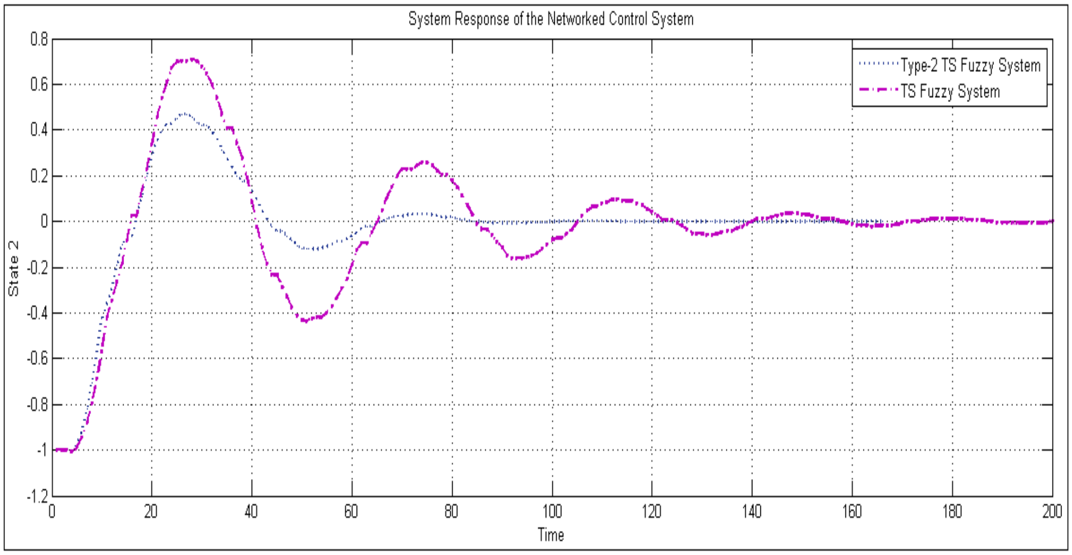

Figure 3.7: Type-2 TS Fuzzy System vs TS Fuzzy System

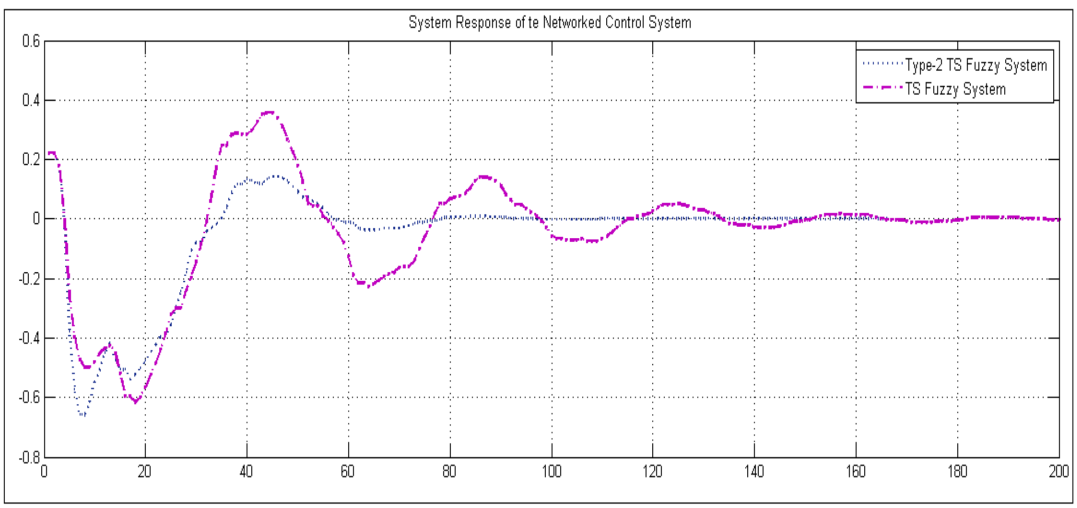

Figure 3.8: Type-2 TS Fuzzy System vs TS Fuzzy System

The response of the system was then plotted for different delays to understand the response change with the change in delays.

The response is plotted first for exponential delay, choosing delay $\phi(t) = 0.1e^{-t}$. The response is shown in the Figure 3-9.

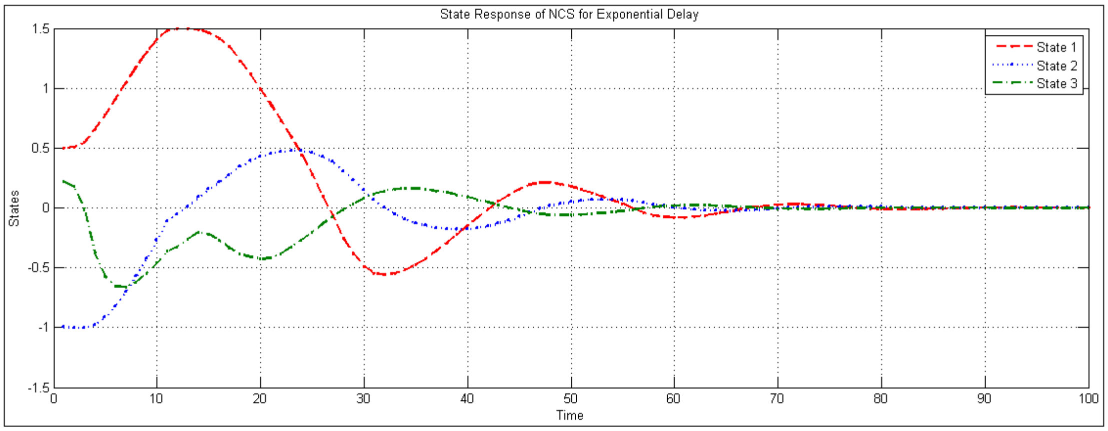

Figure 3.9: State Responses of NCS for Exponential Delay

It can be inferred from the plot that the response for exponential delay is much faster i.e., the settling time is 75 sec which is less than for the other delay i.e., sine which had a settling time of 80 sec.

Now, the response is plotted for step delay. The delay is considered for two cases i.e., unit step delay and step delay with step size of 5. The response is as shown in the figure 3-10, figure 3-11.

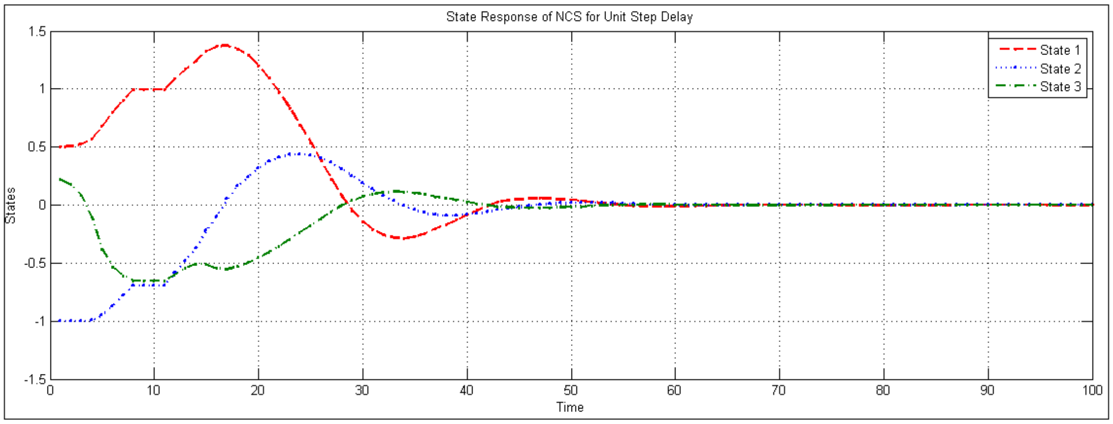

Figure 3.10: State Responses of NCS for Unit Step Delay

From the state response of the system for unit step delay it can be inferred that the settling time is much less i.e., nearly 55 sec and the maximum peak overshoot for the state 1 is also less i.e., nearly 1.4.

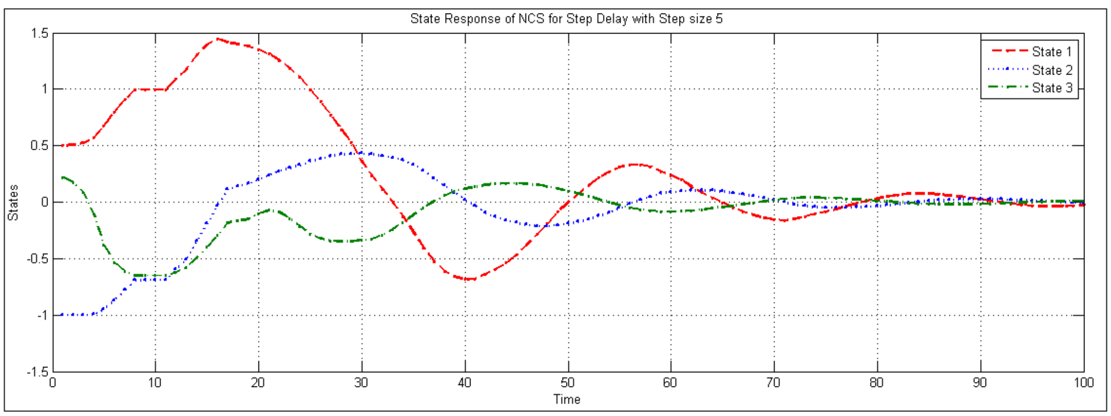

Figure 3.11: State Responses of NCS for Step Delay with Step size 5

From the state response of the system for step delay with step size of 5 it can be inferred that the settling time has increased drastically i.e., nearly 100 sec.

Case 2:

For $\phi_1 = 10$, $\phi_2 = 30$ we get a different set of controller gains that can be obtained as,

$$K_1 = [0.2097 \quad 0.1166 \quad 0.06611]$$

$$K_2 = [3.2642 \quad 2.4906 \quad 3.8442]$$

$$K_3 = [0.3504 \quad 0.0751 \quad 0.1802]$$

Based on the controller gains, the simulation results for the states are shown in Figure 3.12.

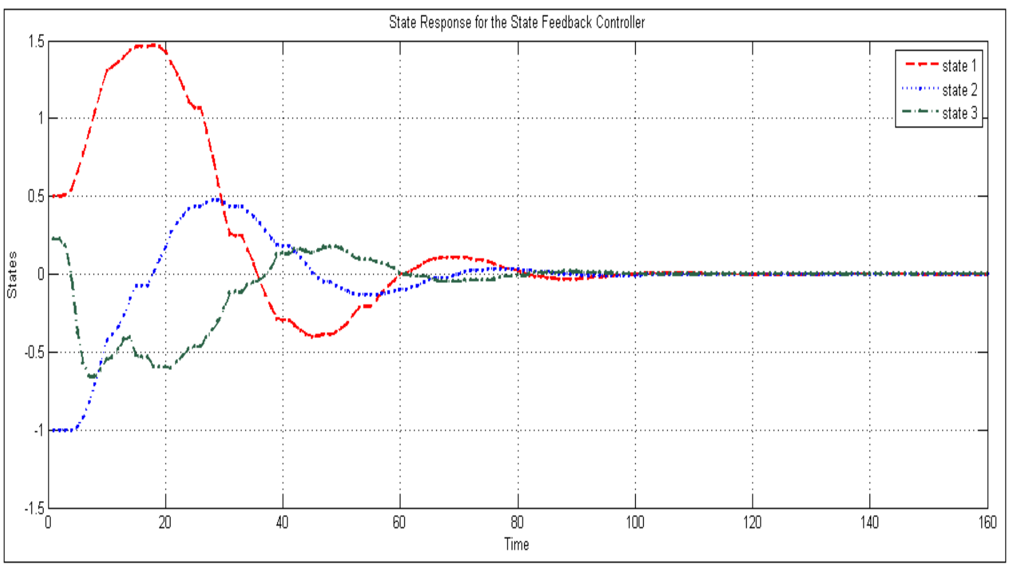

Figure 3.12: State Responses of the State Feedback Controller

It can be inferred from the response that, the system response in the delay range $\phi_1 = 10$, $\phi_2 = 30$ has a slightly sluggish response ie., the settling time is around 95 sec for the given delay $\phi(t) = 1.2 + 0.8|\sin(t)|$.

Now, the results of the Type-2 Fuzzy Logic Controller are compared with that of the Type-1 Fuzzy Logic Controller. The results are as shown in Figures 3.13-3.15.

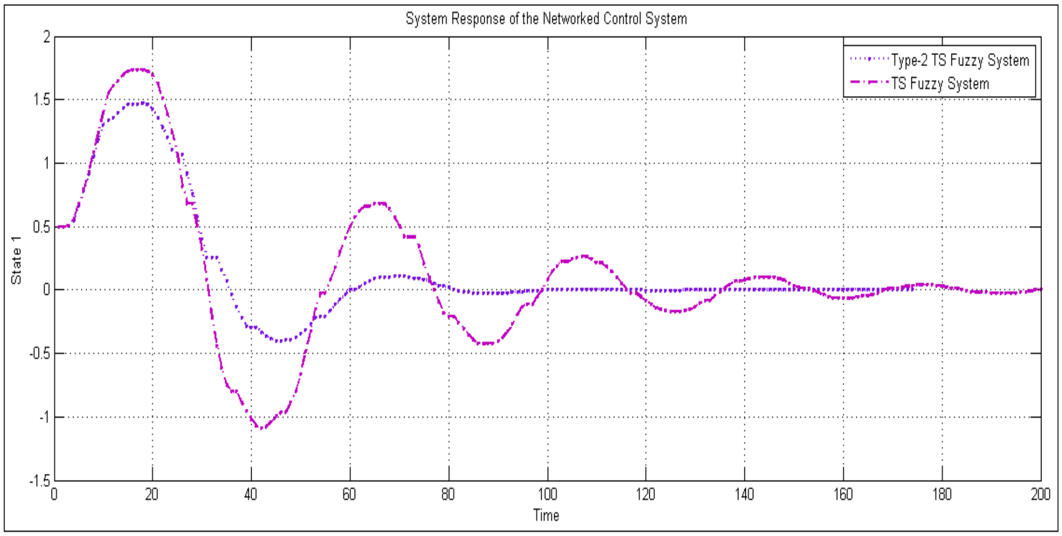

Figure 3.13: Type-2 TS Fuzzy System vs TS Fuzzy System

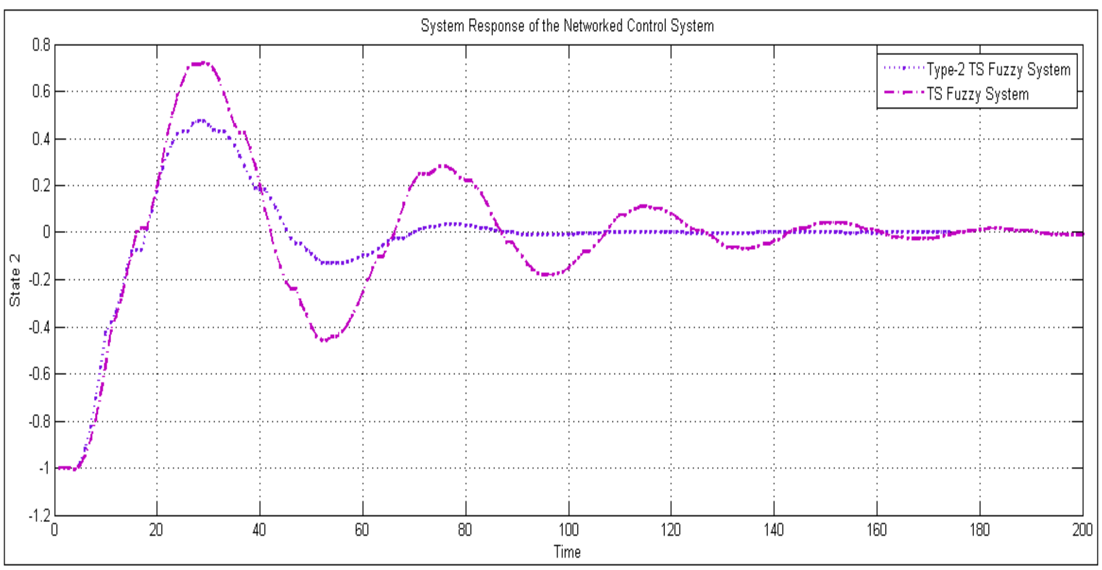

Figure 3.14: Type-2 TS Fuzzy System vs TS Fuzzy System

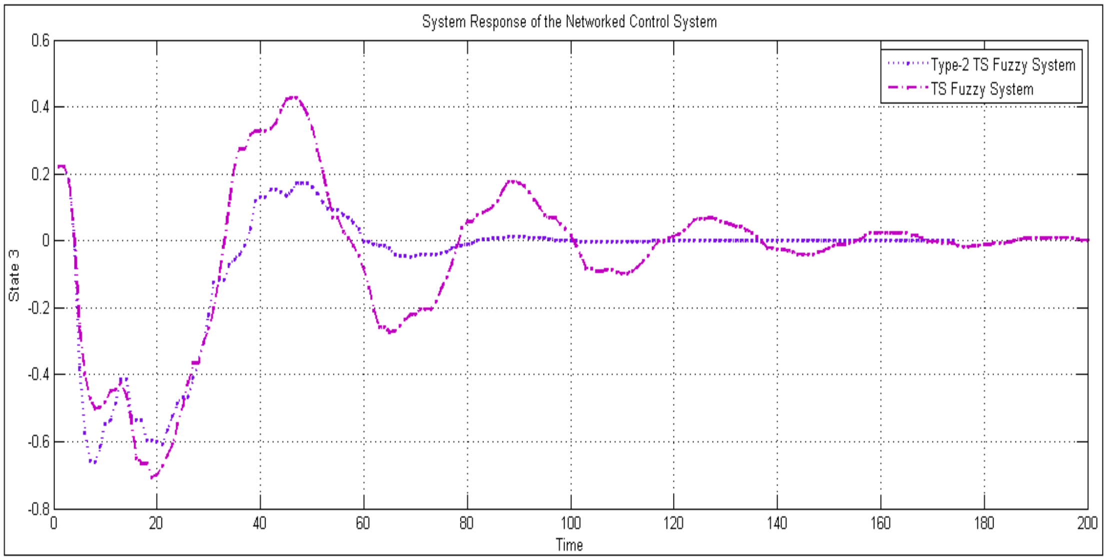

Figure 3.15: Type-2 TS Fuzzy System vs TS Fuzzy System

The results verify that the closed-loop system is stable and the dynamic response of the system responds better under situations of delay and packet loss.

The response of the system is plotted for two cases i.e., for $\phi_1 = 1.2$, $\phi_2 = 2$ and $\phi_1 = 10$, $\phi_2 = 30$. The response of the system is better for the first case as the settling time for all the states is less (i.e., 80 sec) than compared to the second case (i.e., 95 sec).The response is also plotted for $\phi_1 = 0.1$, $\phi_2 = 0.3$ but the system response was unstable.

The response of the Type-2 TS FLC for NCS is then compared to the TS Fuzzy system, the simulation results show that the response of the Type-2 TS Fuzzy system is better than TS Fuzzy system. The settling time and maximum peak overshoot for Type 2 FLC was much less than TS Fuzzy system for both the cases. In both the cases, the settling time for all the states for Type-2 FLC was around 80-90 sec whereas the settling time for TS Fuzzy System was around 200 sec.

The response of the system was then plotted for different delays to understand the response change with the change in delays.

The response is plotted first for exponential delay, choosing delay $\phi(t) = 0.1e^{-t}$. The response is shown in the fig. 3-16.

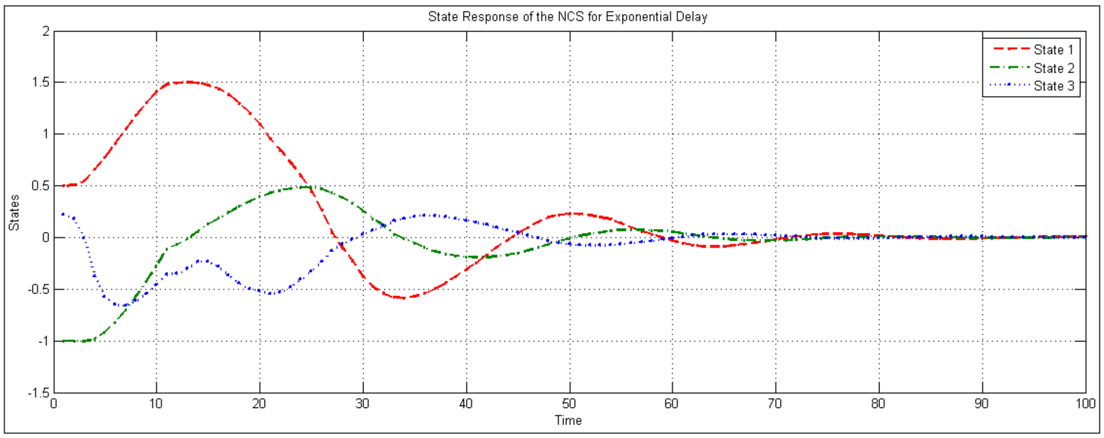

Figure 3.16: State Responses of NCS for Exponential Delay

It can be inferred from the plot that the response for exponential delay is much faster i.e., the settling time is 75 sec which is less than for the other delay i.e., sine which had a settling time of 95 sec.

Now, the response is plotted for step delay. The delay is considered for two cases i.e., unit step delay and step delay with step size of 5. The response is as shown in the figure 3-17, figure 3-18.

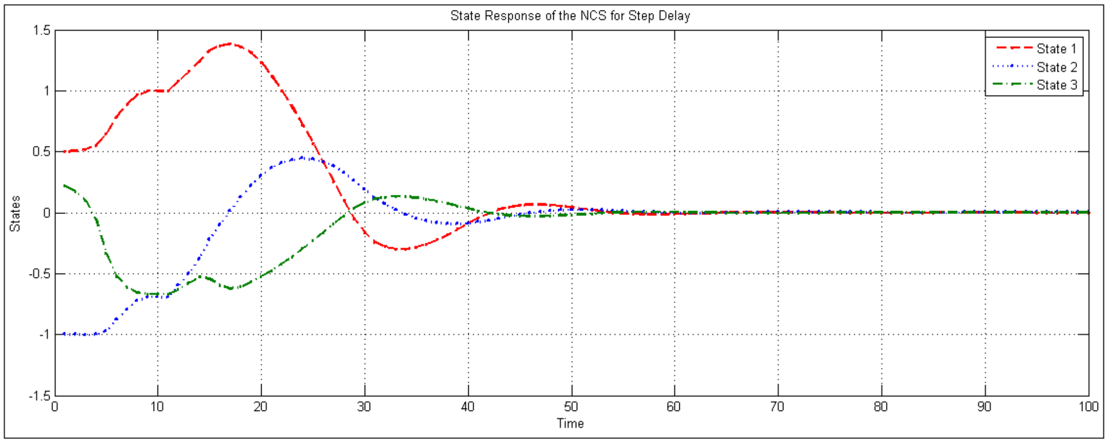

Figure 3.17: State Responses of NCS for Unit Step Delay

From the state response of the system for unit step delay it can be inferred that the settling time is much less i.e., nearly 55 sec and the maximum peak overshoot for the state 1 is also less i.e., nearly 1.4.

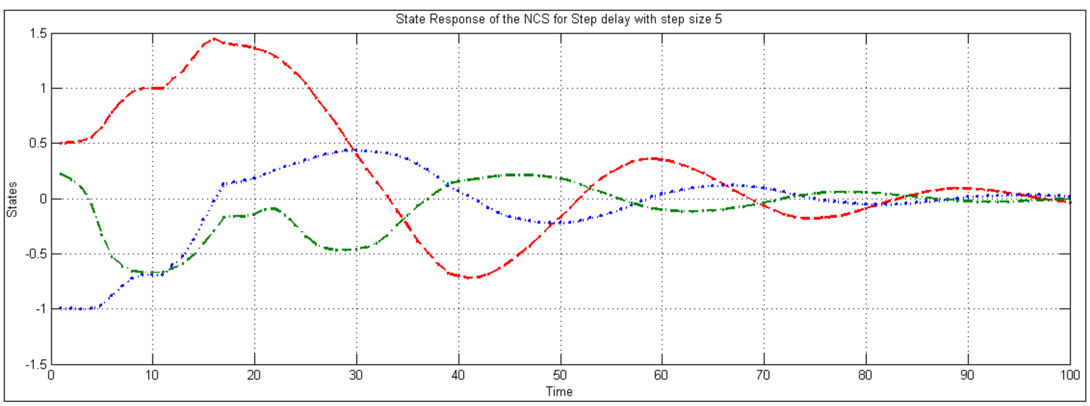

Figure 3.18: State Responses of NCS for Step Delay of Step Size 5

From the state response of the system for step delay with step size of 5 it can be inferred that the settling time has increased drastically i.e., nearly 100 sec.

Case 3:

For $\phi_1 = 1,\ \phi_2 = 10$ we get a different set of controller gains that can be obtained as,

$$K_1 = [-0.0081 \quad -4.5281 \quad 0.5107]$$

$$K_2 = [1.1481 \quad 6.4070 \quad 1.3876]$$

$$K_3 = [0.1370 \quad -0.1611 \quad 0.4788]$$

Based on the controller gains, the simulation results for the states are shown in Figure 3.19.

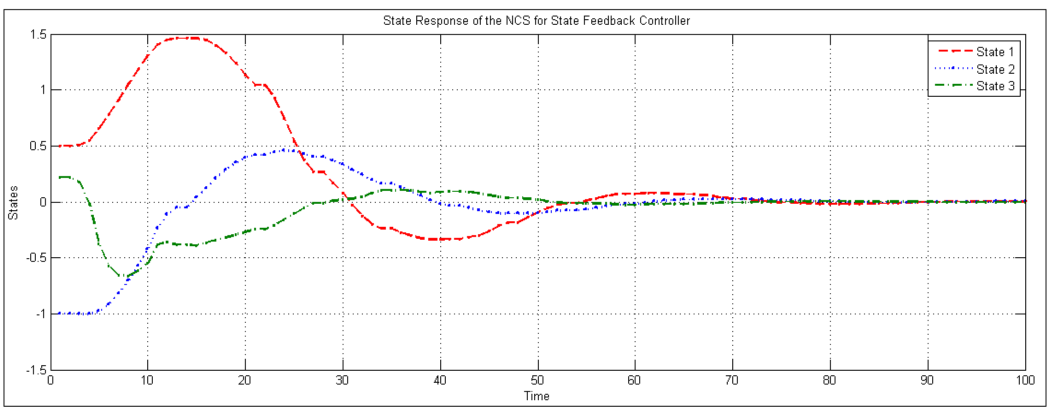

Figure 3.19: State Responses of the State Feedback Controller

The response of the system is better for this case i.e., the settling time for all the states is around 75 sec, whereas the settling time for case 1 is 80 sec and for the case 2 is 95 sec.

The response of the system was then plotted for different delays to understand the response change with the change in delays.

The response is plotted first for exponential delay, choosing delay $\phi(t) = 0.1e^{-t}$. The response is shown in the Figure 3-20.

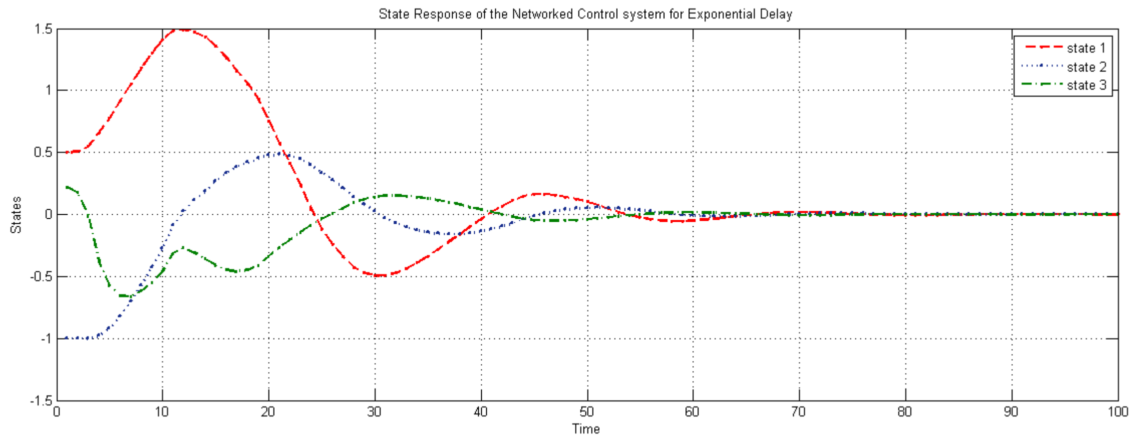

Figure 3.20: State Response for Exponential Delay

It can be inferred from the plot that the response for exponential delay is much faster i.e., the settling time is 70 sec which is less than for the other delay i.e., sine which had a settling time of 90 sec.

Now, the response is plotted for step delay. The delay is considered for two cases i.e., unit step delay and step delay with step size of 5. The response is as shown in the figure 3-21, figure 3-22.

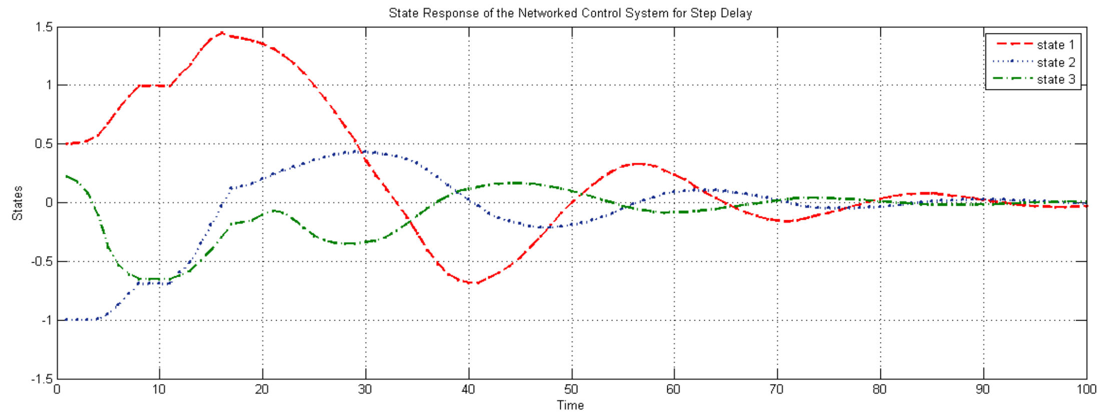

Figure 3.21: State Response of the NCS for Step delay of step size 5

From the state response of the system for step delay with step size of 5 it can be inferred that the settling time has increased drastically i.e., nearly 100 sec.

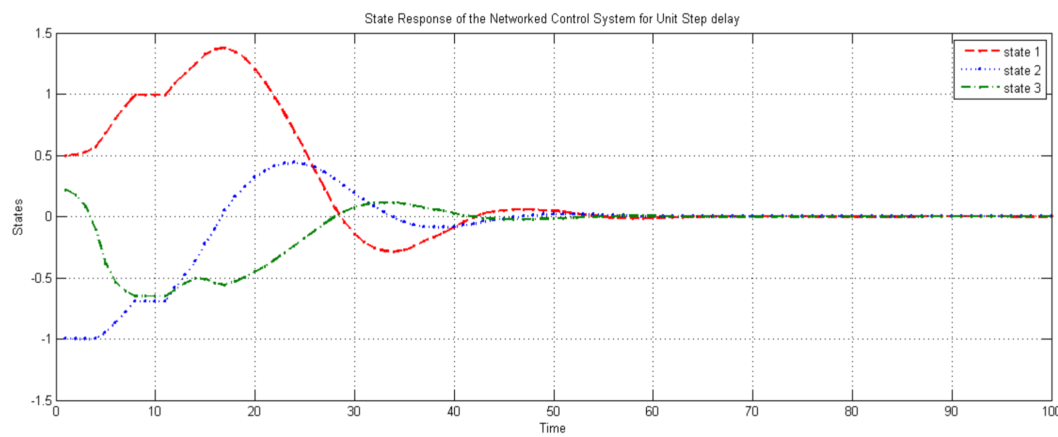

Figure 3.22: State Response of the NCS for unit Step delay

From the state response of the system for unit step delay it can be inferred that the settling time is much less i.e., nearly 55 sec and the maximum peak overshoot for the state 1 is also less i.e., nearly 1.3.

Comparison of State Feedback Control Design with that of the Control Design in [43]

The results of the State Feedback controller design explained in this chapter are compared with that of the state feedback control design results in [43]. The results are shown in Figures 3-23, 3-24, 3-25.

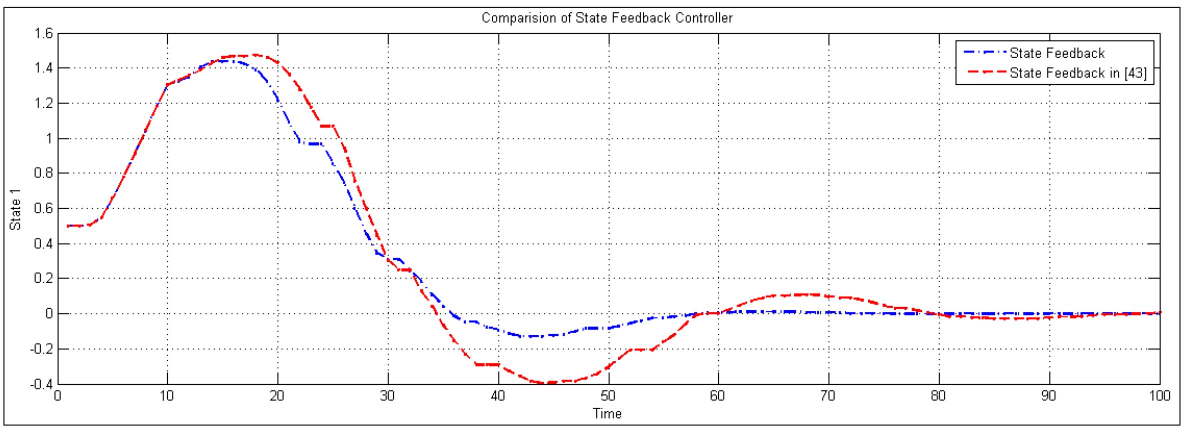

Figure 3.23: Comparison of State Feedback Controller for State 1

It can be inferred from the above Figure 3-23 that, the response of the state feedback controller developed for state 1 in this thesis is much better than the response of the state feedback control in [43]. The settling time is much less i.e., around 65 sec than compared to 95 sec in the case of state feedback control response in [43].

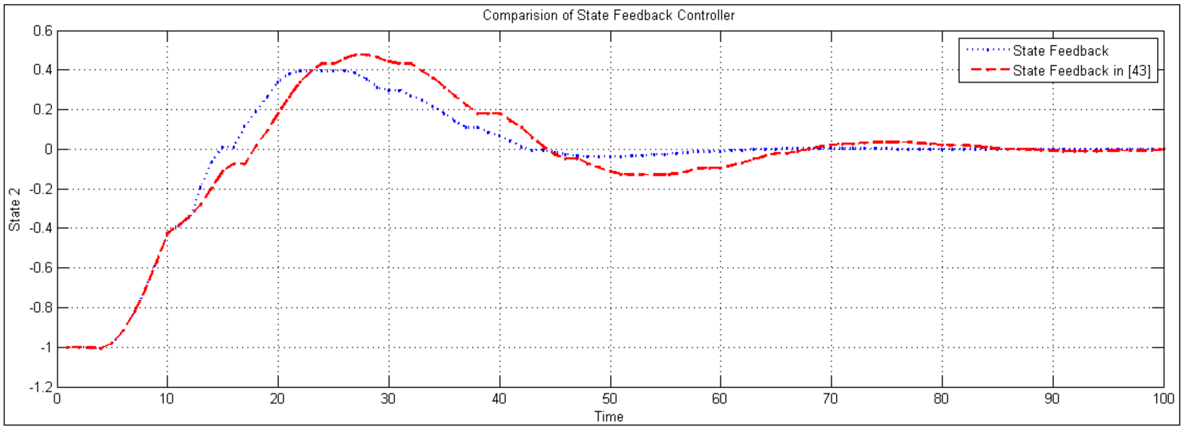

Figure 3.24: Comparison of State Feedback Controller for State 2

It can be inferred from the above Figure 3-24 that, the response of the state feedback controller developed for state 2 in this thesis is much better than the response of the state feedback control in [43]. The settling time is much less i.e., around 65 sec than compared to 95 sec in the case of state feedback control response in [43].

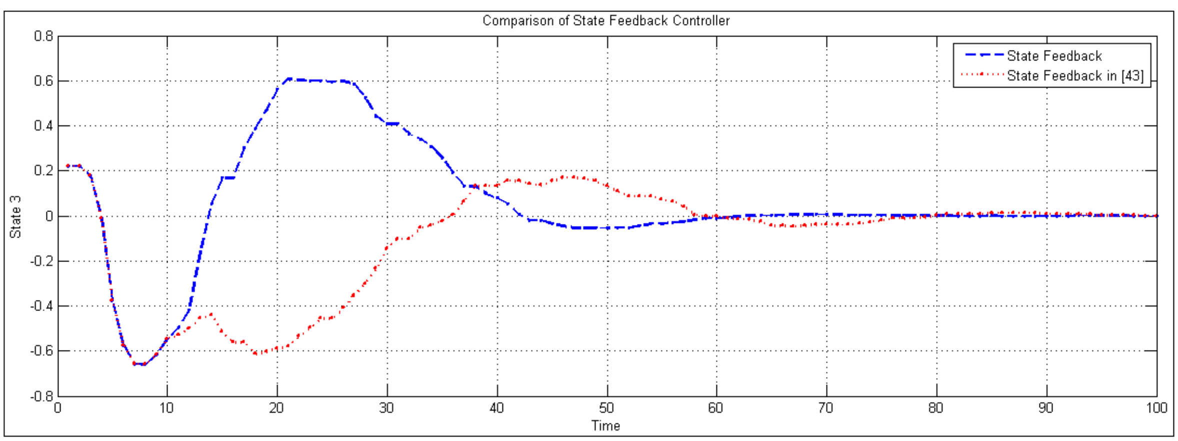

Figure 3.25: Comparison of State Feedback Controller for State 3

It can be inferred from the above Figure 3-25 that, the response of the state feedback controller developed in this thesis is much better than the response of the state feedback control in [43]. The settling time is much less i.e., around 65 sec than compared to 95 sec in the case of state feedback control response in [43].

3.6 Conclusions

A State Feedback Controller based on Type-2 Fuzzy Logic for Networked Control Systems with delays is designed in this chapter. For defining the controller gains through Linear Matrix Inequality for the state feedback controller a Lyapunov Krasovskii functional was considered. We considered up to five terms for the functional. The main focus is to build a base for designing an observer based controller. To validate the design simulations were carried out and the results are compared with the TS Fuzzy System. The results were plotted for two cases. The results prove that the Type-2 TS FLC performs better than the TS Fuzzy System and the simulation results reflect the effectiveness of the proposed controller.

Chapter 4

DESIGN OF TYPE 2 FLC OBSERVER BASED NETWORKED CONTROL SYSTEM

4.1 Introduction

Due to recent developments in industrial and communication technologies, most of the control applications in the industry have been dedicating much of its attention to networked control systems. It is almost apparent that the stabilization problem of networked control systems has been discussed in the presence of network constraints like delay in time and loss in data [43, 44]. Furthermore, necessary and sufficient conditions for NCSs stability have been studied for state and output feedback [45-47].

It is known that data can be transferred across communication networks in packet form; this makes it likely to cover packets time delay and loss in data by sending a sequence control in one packet for routing control according to the last network condition. Moreover, transmitted packet can be lost completely because of the unreliable nature of the communication channels. As a result, the transmitted packets between a sensor to controller and from the controller to actuator are lost randomly. Practically, these communication properties may affect the estimation and control performance [48, 49].

This chapter deals with the estimation schemes in Networked Control Systems (NCS). A class of observer based stabilizing controller of Networked Control Systems is considered with non-stationary packet dropout. Moreover, the control and observation signals are modeled by two mutually independent random variables. The Observer based controller is designed to stabilize the Networked Control System, where a sufficient condition for stability is driven in terms of using Linear Matrix Inequality (LMIs).

In this chapter, we propose an extension of the work of [50] by designing a state observer based controller for a NNCS on the existing packet loss and delays. The type of NNCS will be a state observer based controller. The state observer is designed based on the Type-2 Fuzzy Logic Controller. The observer is integrated by forming Linear Matrix Inequality for deriving the stability conditions. The block diagram for the observer based controller is depicted in Figure 4.1.

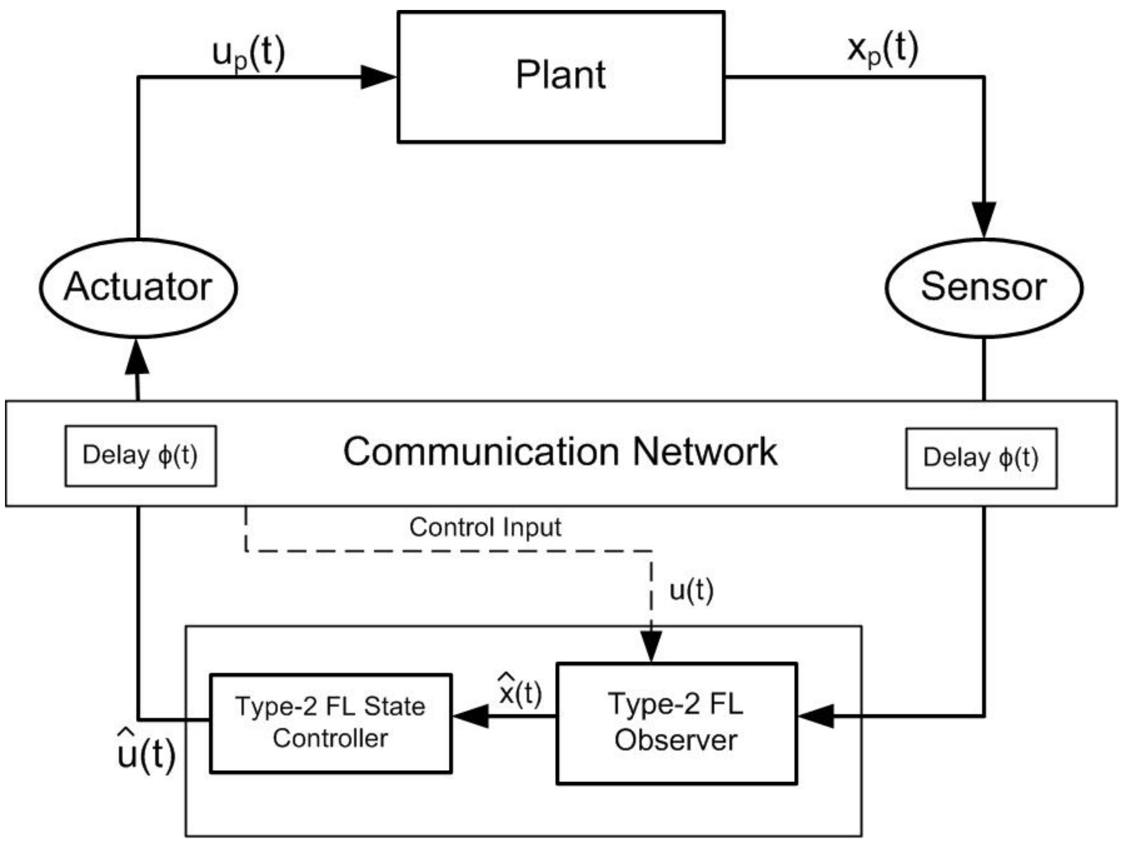

Figure 4.1: Block Diagram of Observer Based Controller

4.2 Observer-based feedback design

To design an observer for the Networked Control System we design the following output feedback controller:

$$\dot{\hat{x}}(t) = \sum_{i=1}^{r} h_i(z(t))\{A_i\hat{x}(t) + A_{di}\hat{x}(t-\phi(t)) + B_i u(t) + L_i C_2(x(t) - \hat{x}(t))\} \quad (4.1)$$

$$u(t) = \sum_{j=1}^{r} h_j(z(t))K_j\hat{x}(t-\phi(t))$$

Denoting $e(t) = x(t) - \hat{x}(t)$, we can form an augmented model based on Eq. (3.9) and Eq. (4.1) as

$$\dot{x}(t) = \sum_{i=1}^{r} \tilde{h}_i\tilde{h}_j\{A_i x(t) + A_{di}x(t-\phi(t)) + B_i K_j x(t-\phi(t))\} \quad (4.2)$$

Eq. (4.1) can be written as,

$$\dot{\hat{x}}(t) = \sum_{i=1}^{r}\sum_{j=1}^{r} h_i(z(t))h_j(z(t))\{A_i\hat{x}(t) + A_{di}\hat{x}(t-\phi(t)) + B_i K_j\hat{x}(t-\phi(t)) + L_i C_2(x(t) - \hat{x}(t))\}$$

and we know that $e(t) = x(t) - \hat{x}(t)$, then $\dot{e}(t) = \dot{x}(t) - \dot{\hat{x}}(t)$,

Now,

$$\dot{e}(t) = \sum_{i=1}^{r}\sum_{j=1}^{r} \begin{array}{l} \tilde{h}_i\tilde{h}_j\{A_i x(t) + A_{di}x(t-\phi(t)) + B_i K_j x(t-\phi(t) \\ - A_i\hat{x}(t) - A_{di}\hat{x}(t-\phi(t)) - B_i K_j\hat{x}(t-\phi(t)) - L_i C_2(x(t) - \hat{x}(t))\} \end{array}$$

$$\dot{e}(t) = \sum_{i=1}^{r}\sum_{j=1}^{r} \tilde{h}_i\tilde{h}_j\{A_i e(t) + A_{di}e(t-\phi(t)) + B_i K_j e(t-\phi(t)) - L_i C_2 e(t)\} \quad (4.3)$$

Now, we formulate the augmented model based on Eq. (4.2) and (4.3)

$$\dot{\xi}(t) = \bar{A}_i\xi(t) + \bar{A}_{di}\xi(t-\phi(t)) + \bar{A}_{\phi}\xi(t-\phi(t)) \quad (4.4)$$

With

$$\overline{A}_i = \begin{bmatrix} A_i & 0 \\ 0 & A_i - L_i C_2 \end{bmatrix}, \overline{A}_{di} = \begin{bmatrix} A_{di} & 0 \\ 0 & A_{di} \end{bmatrix}, \overline{A}_{\phi} = \begin{bmatrix} B_i K_j & 0 \\ 0 & B_i K_j \end{bmatrix}$$

and

$$\xi(t) = \begin{bmatrix} x^T(t) & e^T(t) \end{bmatrix}^T$$

Now, we design the type-2 fuzzy obsrver-based control for the system, which is summarised in the following theorem.

4.3 Main Results:

Theorem 3: *For any given scalars* $\phi_1 > 0, \phi_2 > 0$, $\mu_1 > 0$, $\mu_2 > 0$, $\tau_1 > 0$, $\tau_2 > 0$, *closed loop system is asymptotically stable, if there exists positive matrices* $P, Q_1, Q_2, Z_1, Z_2, \zeta, \widetilde{G}, F_i, Y_i$, *with appropriate dimensions, such that* $\Lambda < 0$

$$\Lambda = \begin{bmatrix} \Lambda_{11} & \Lambda_{12} & \Lambda_{13} & 0 & \Lambda_{15} \\ \Lambda_{21} & \Lambda_{22} & \Lambda_{23} & \Lambda_{24} & \Lambda_{25} \\ \Lambda_{31} & \Lambda_{32} & \Lambda_{33} & 0 & 0 \\ 0 & \Lambda_{42} & 0 & \Lambda_{44} & 0 \\ \Lambda_{51} & \Lambda_{52} & 0 & 0 & \Lambda_{55} \end{bmatrix} \tag{4.5}$$

$$\Lambda_{11} = Q_1 + Q_2 - Z_1 + \widetilde{A}_i^T + \widetilde{A}_i$$

$$\Lambda_{12} = \widetilde{B}_i + \widetilde{A}_{di}^T + \tau_1 \widetilde{A}_i^T$$

$$\Lambda_{13} = Z_1$$

$$\Lambda_{15} = P - \widetilde{G}^T + \tau_2 \widetilde{A}_i^T$$

$$\Lambda_{21} = \widetilde{B}_i^T + \widetilde{A}_{di}^T + \tau_1 \widetilde{A}_i$$

$$\Lambda_{22} = -2Z_2 + \tau_1 \tilde{A}_{di}^{\ T} + \tau_1 \tilde{A}_{di} + \tau_1 \tilde{B}_i + \tau_1 \tilde{B}_i^{\ T}$$

$$\Lambda_{23} = Z_2^{\ T}$$

$$\Lambda_{24} = Z_2$$

$$\Lambda_{25} = -\tau_1 \tilde{G} + \tau_2 \tilde{A}_{di}^T + \tau_2 \tilde{B}_i^T$$

$$\Lambda_{31} = Z_1^{\ T}$$

$$\Lambda_{32} = Z_2^T$$

$$\Lambda_{33} = -(1-\mu_1)Q_1 - Z_1 - Z_2$$

$$\Lambda_{42} = Z_2^T$$

$$\Lambda_{44} = -(1-\mu_2)Q_2 - Z_2$$

$$\Lambda_{51} = P^T - \tilde{G}^T + \tau_2 \tilde{A}_i$$

$$\Lambda_{52} = -\tau_1 \tilde{G}^T + \tau_2 \tilde{A}_{di} + \tau_2 \tilde{B}_i$$

$$\Lambda_{55} = \phi_1^{\ 2} Z_1 + \phi_r^{\ 2} Z_2 - \tau_2 \tilde{G} - \tau_2 \tilde{G}^T$$

$$\tilde{A}_i = \begin{bmatrix} A_i \rho & A_i G \\ 0 & A_i G - L_i C_2 G \end{bmatrix}, \ \tilde{A}_{di} = \begin{bmatrix} A_{di}\rho & A_{di} G \\ 0 & A_{di} G \end{bmatrix}, \ \tilde{B}_i = \begin{bmatrix} B_i K_j \rho & B_i K_j G \\ 0 & B_i K_j G \end{bmatrix},$$

$$\hat{G} = \begin{bmatrix} \hat{G}_{11} & 0 \\ 0 & \hat{G}_{22} \end{bmatrix}, \ G = V\hat{G}V^T, \ \ \tilde{G} = \begin{bmatrix} \rho & G \\ 0 & G \end{bmatrix}$$

Then the desired controller and observer gains are given by $K_i = Y_i \rho^{-1}$ *and* $L_i = F_i U S_0 \hat{G}_{11}^{-1} S_0^{-1} U^T$ *respectively, where U, V and* S_0 *come from SVD decomposition of* C_2.

Proof: Under conditions of the theorem, it follows from $\Lambda < 0$ that $\tilde{G}$ is nonsingular. Thus ρ and G are also nonsingular. Based on the Assumption 1 and Lemma 1, we can write,

$$L_i C_2 G = L_i \hat{G}_{11} C_2 \tag{4.6}$$

Since in the Eq. (4.6) there are two unknowns L_i and $\hat{G}_{11}$, so Λ in Eq. (4.5) is bilinear. Now based on the SVD decomposition of C_2 we can write $L_i \hat{G}_{11} = F_i$ and we can also write $K_i \rho = Y_i$.

Then the augmented matrices can be written as,

$$\sum_{i=1}^{r}\sum_{j=1}^{r} h_i h_j \tilde{A}_i = \bar{A}_i \tilde{G} = \begin{bmatrix} A_i & 0 \\ 0 & A_i - L_i C_2 \end{bmatrix} \times \begin{bmatrix} \rho & G \\ 0 & G \end{bmatrix} = \begin{bmatrix} A_i \rho & A_i G \\ 0 & A_i G - F_i C_2 \end{bmatrix}$$

$$\sum_{i=1}^{r}\sum_{j=1}^{r} h_i h_j \tilde{A}_{di} = \bar{A}_{di} \tilde{G} = \begin{bmatrix} A_{di} & 0 \\ 0 & A_{di} \end{bmatrix} \times \begin{bmatrix} \rho & G \\ 0 & G \end{bmatrix} = \begin{bmatrix} A_{di} \rho & A_{di} G \\ 0 & A_{di} G \end{bmatrix}$$

$$\sum_{i=1}^{r}\sum_{j=1}^{r} h_i h_j \tilde{B}_i = \bar{A}_{\phi} \tilde{G} = \begin{bmatrix} B_i K_j & 0 \\ 0 & B_i K_j \end{bmatrix} \times \begin{bmatrix} \rho & G \\ 0 & G \end{bmatrix} = \begin{bmatrix} B_i K_j \rho & B_i K_j G \\ 0 & B_i K_j G \end{bmatrix}$$

The remaining proof is similar to that of Theorem 1. If the linear matrix Inequality Eq. (4.5) is satisfied for every i and $\dot{V}(t)$ is negative definite, then the closed-loop networked control system in Eq. (4.4) is asympotically stable. The feedback control gain can be given as $K_i = Y_i \rho^{-1}$ and the observer gain is given as $L_i = F_i U S_0 \hat{G}_{11}^{-1} S_0^{-1} U^T$ .This completes the proof.

To perform the simulation, the sampling time is set to *h*=0.01s, and the initial condition is assumed to be $x_0 = [0.5 \quad -1 \quad 0.22]'$. The network induced delays are defined by the equation as $\phi(t) = 1.2 + 0.8 \,|\sin(t)|$. The constants are set as $\mu_1 = 0.2,\ \mu_2 = 0.3$, $\tau_1 = 0.02$, $\tau_2 = 0.03$.

Case 1:

For $\phi_1 = 1.2$, $\phi_2 = 2$ we get a different set of controller gains that can be are calculated.

Based on the Theorem 3, the LMI is solved using the YALMIP toolbox in MATLAB and the feedback and observer gains are calculated to be,

We consider the values of $\phi_1 = 1.2$, $\phi_2 = 2$ to get the best possible results for delay $\phi(t) = 1.2 + 0.8 \,|\sin(t)|$ we get a different set of controller gains that can be obtained as,

$$K_1 = [-0.3197 \quad 0.0745 \quad 0.3324],$$

$$K_2 = [-1.1038 \quad -0.6780 \quad 2.4863]$$

$$K_3 = [-0.0024 \quad -0.0173 \quad 0.0814]$$

$$L_1 = \begin{bmatrix} 299.6250 \\ 300.5465 \\ 300.7584 \end{bmatrix},\ L_2 = \begin{bmatrix} 291.0118 \\ 291.4459 \\ 291.7925 \end{bmatrix},\ L_3 = \begin{bmatrix} 306.7005 \\ 306.9056 \\ 307.2654 \end{bmatrix}$$

The simulation results are shown in Figures 4.2. The input Response is shown in the Figure 4-3.

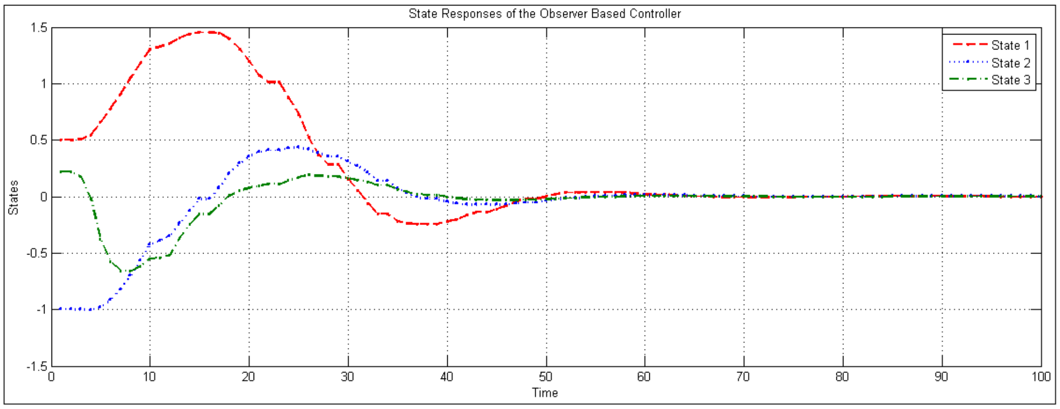

Figure 4.2: State Responses for the Observer based Controller

It can be inferred from the response in Figure 4-2, that the system response is much better in the delay range of $\phi_1 = 1.2$, $\phi_2 = 2$ ie., the settling time is around 60 sec which is supposed to be the best response for the delay $\phi(t) = 1.2 + 0.8|\sin(t)|$.

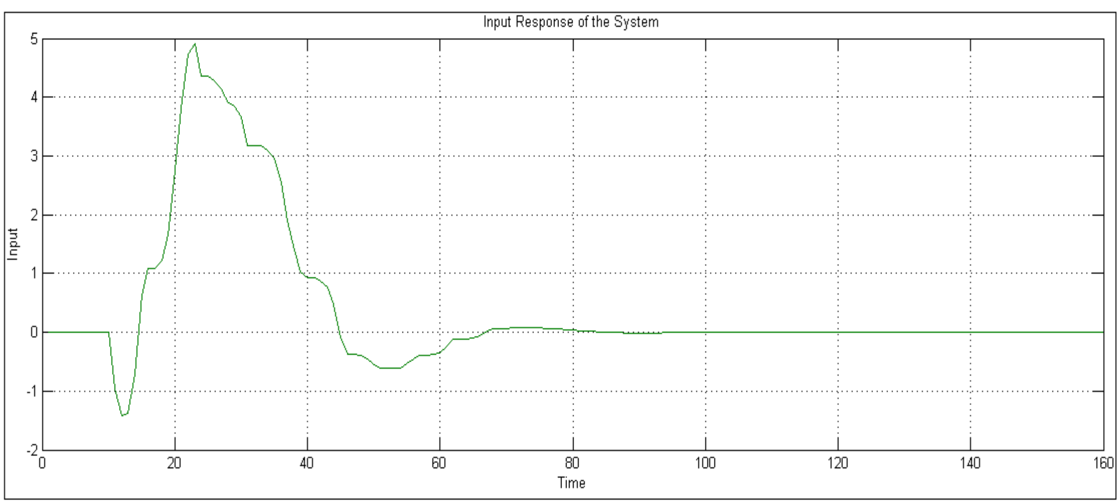

Figure 4.3:Control Input Response

Now, the results of the Type-2 Fuzzy Logic Controller are compared with that of the Type-1 Fuzzy Logic Controller. The results are as shown in Figures 4.4-4.6.

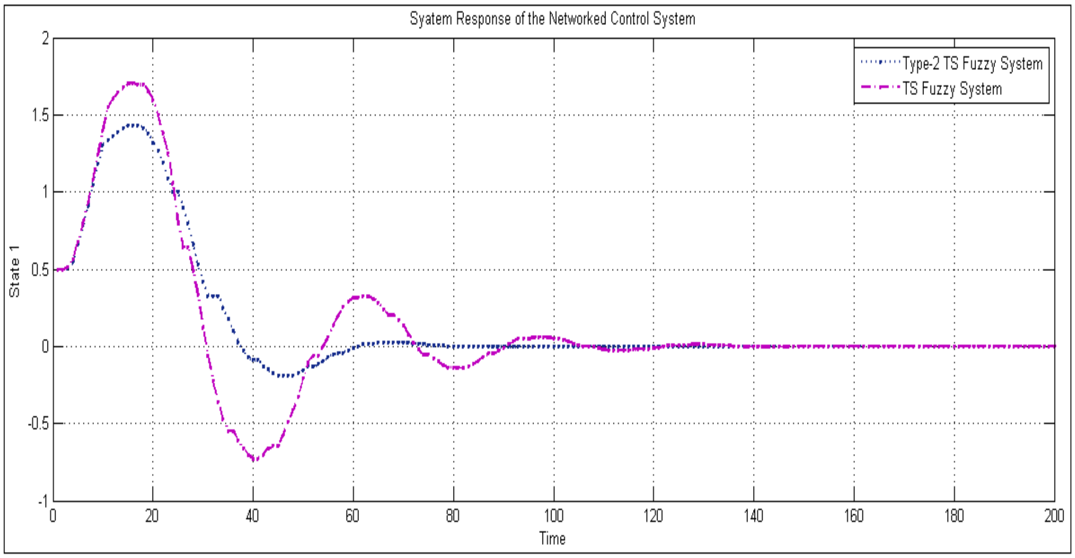

Figure 4.4: Type-2 TS Fuzzy System vs TS Fuzzy System

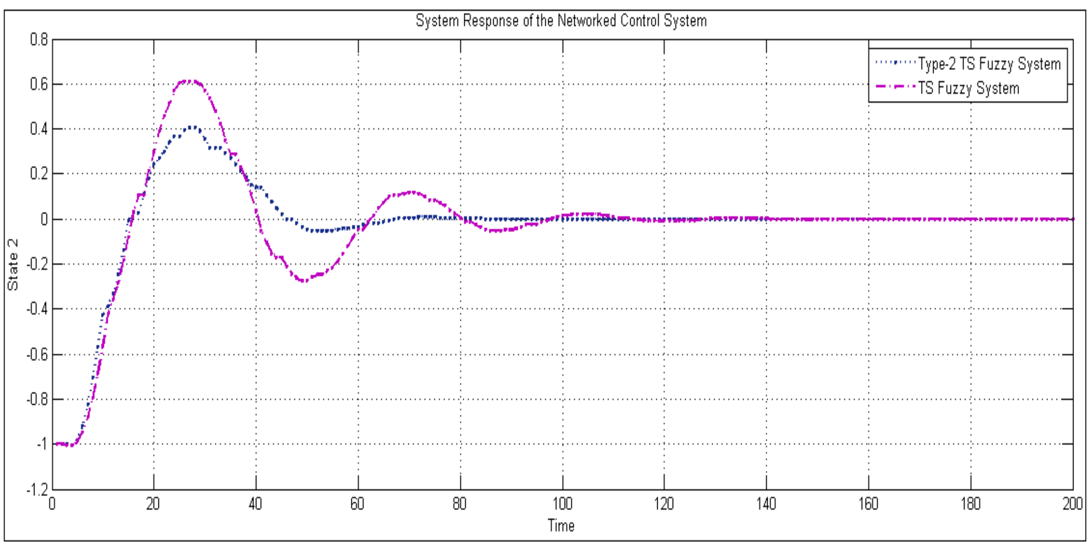

Figure 4.5: Type-2 TS Fuzzy System vs TS Fuzzy System

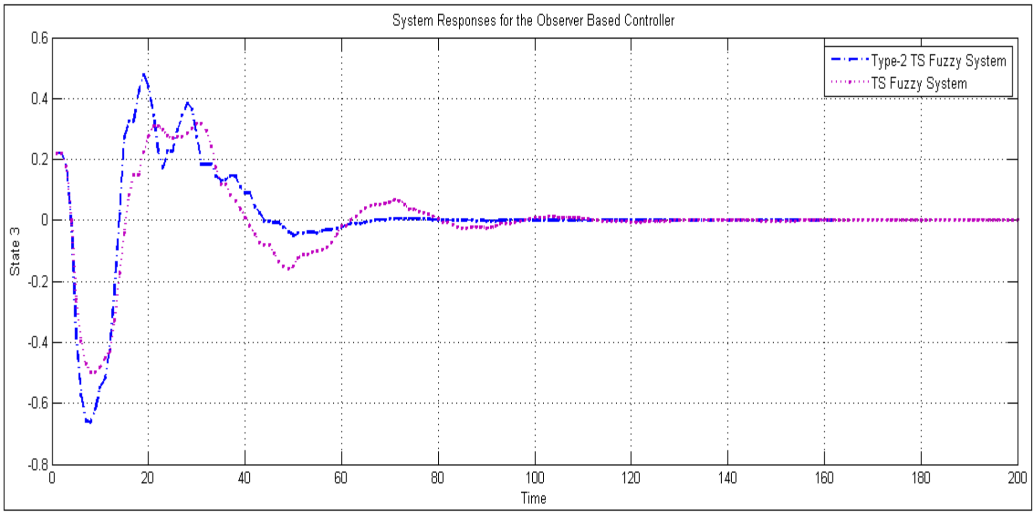

Figure 4.6: Type-2 TS Fuzzy System vs TS Fuzzy System

The response of the system was then plotted for different delays to understand the response change with the change in delays.

The response is plotted first for exponential delay, choosing delay as $\phi(t) = 0.1e^{-t}$. The response is shown in the Figure 4-7.

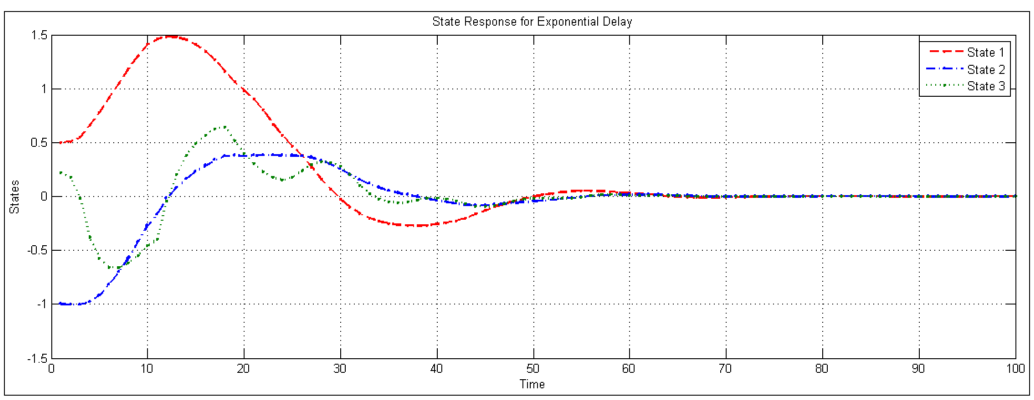

Figure 4.7: State Response for Exponential Delay

It can be inferred from the plot that the response for exponential delay is almost similar i.e., the settling time is 60 sec which is same for the other delay i.e., sine which had a settling time of 60 sec.

Now, the response is plotted for step delay. The delay is considered for two cases i.e., unit step delay and step delay with step size of 5. The response is as shown in the Figure 4-8, Figure 4-9.

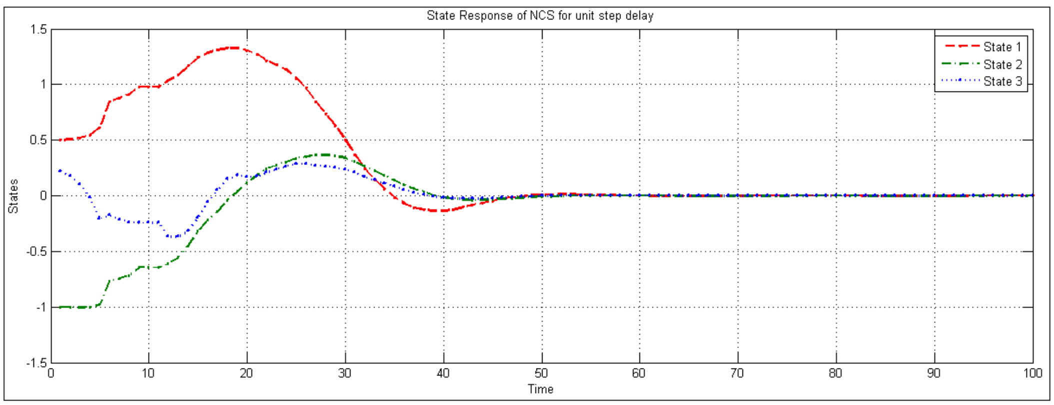

Figure 4.8: State Response for Unit Step Delay

From the state response of the system for unit step delay it can be inferred that the settling time is much less i.e., nearly 50 sec and the maximum peak overshoot for the state 1 is also less i.e., nearly 1.3.

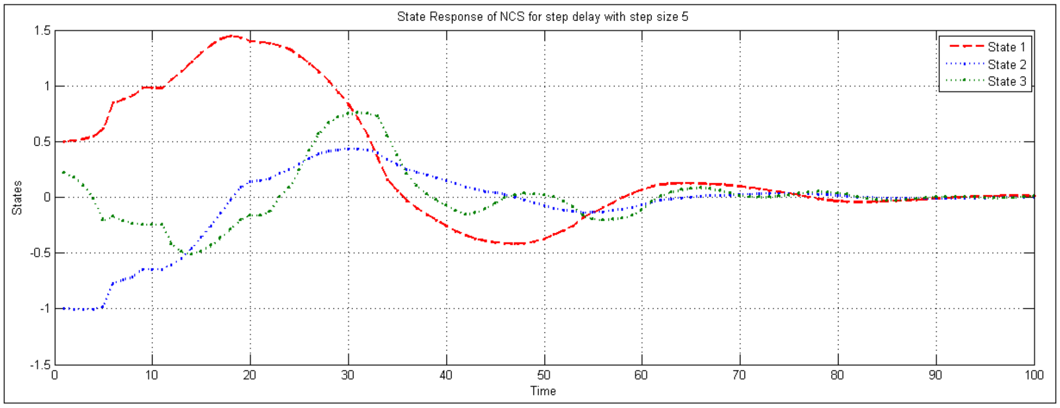

Figure 4.9: State Response for Step Delay with Step Size 5

From the state response of the system for step delay with step size of 5 it can be inferred that the settling time has increased drastically i.e., nearly 100 sec.

Case 2:

For $\phi_1 = 10$, $\phi_2 = 30$ we get a different set of controller gains can be obtained as,

$$K_1 = \begin{bmatrix} -0.7910 & 0.1648 & 00.6684 \end{bmatrix},$$

$$K_2 = \begin{bmatrix} -4.1654 & -1.4918 & 6.0137 \end{bmatrix}$$

$$K_3 = \begin{bmatrix} -0.2288 & -0.1852 & 0.4543 \end{bmatrix}$$

$$L_1 = \begin{bmatrix} 43.0733 \\ 44.0876 \\ 45.1429 \end{bmatrix},\ L_2 = \begin{bmatrix} 34.3065 \\ 34.5285 \\ 35.9215 \end{bmatrix},\ L_3 = \begin{bmatrix} 36.5057 \\ 36.5285 \\ 37.6521 \end{bmatrix}$$

The simulation results are shown in Figures 4.10.

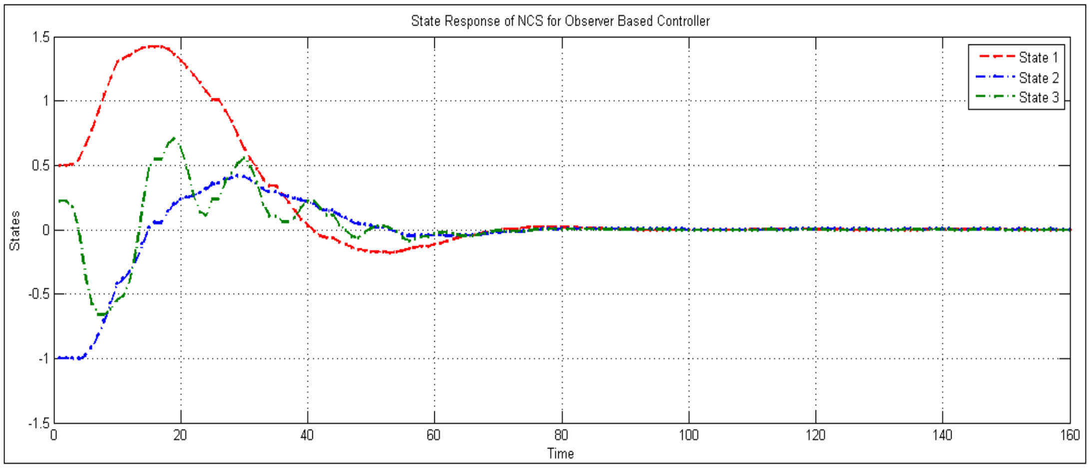

Figure 4.10: System Response for the Observer based Controller

It can be inferred from the response in Figure 4-10, that the system response is more sluggish in the delay range of $\phi_1 = 10$, $\phi_2 = 30$ ie., the settling time is around 80 sec which is for the delay $\phi(t) = 1.2 + 0.8|\sin(t)|$.

Now, the results of the Type-2 Fuzzy Logic Controller are compared with that of the Type-1 Fuzzy Logic Controller. The results are as shown in Figures 4.11-4.13.

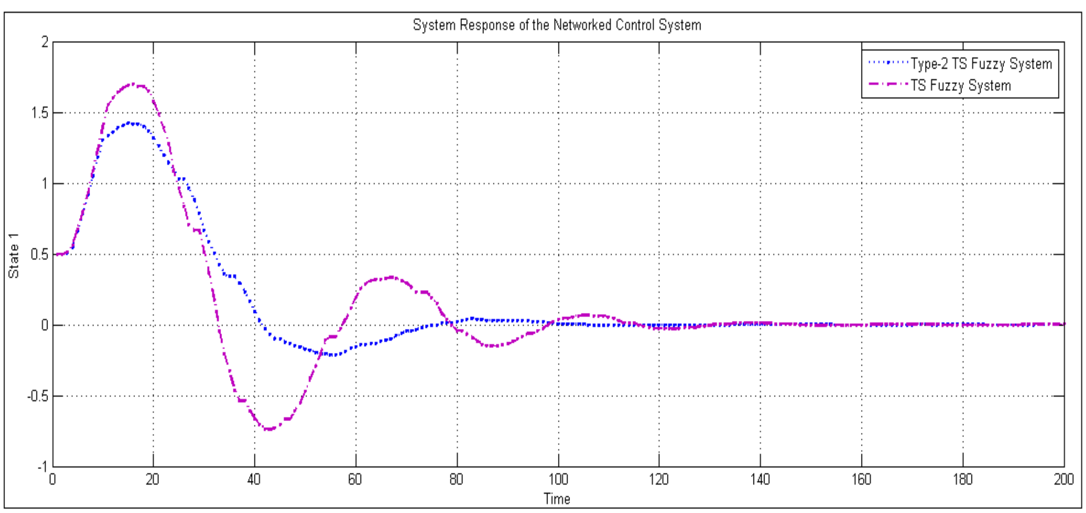

Figure 4.11: Type-2 TS Fuzzy System vs TS Fuzzy System

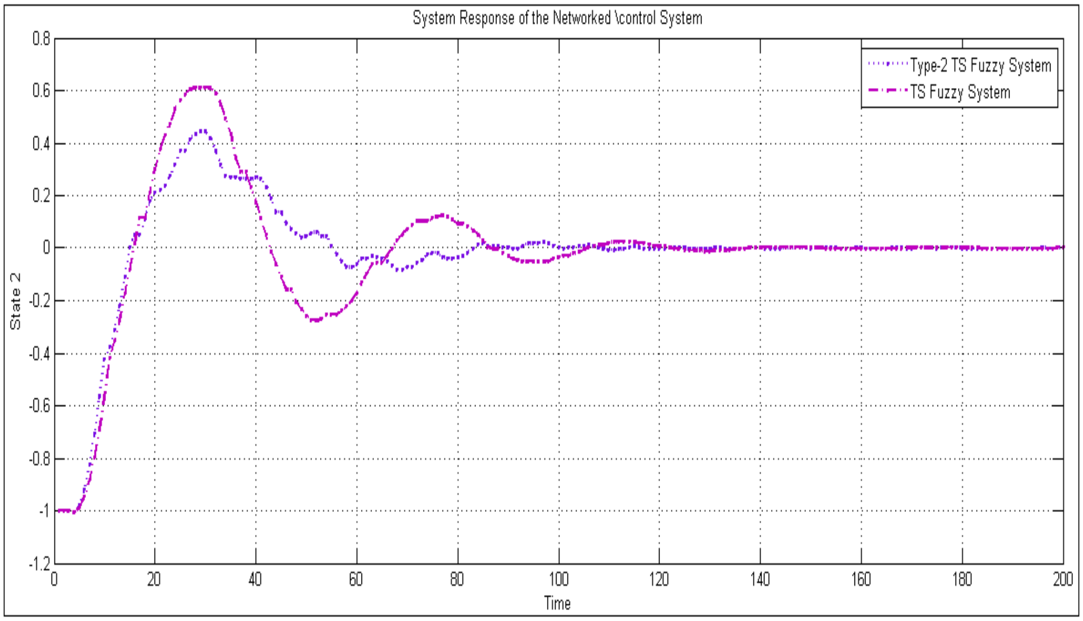

Figure 4.12: Type-2 TS Fuzzy System vs TS Fuzzy System

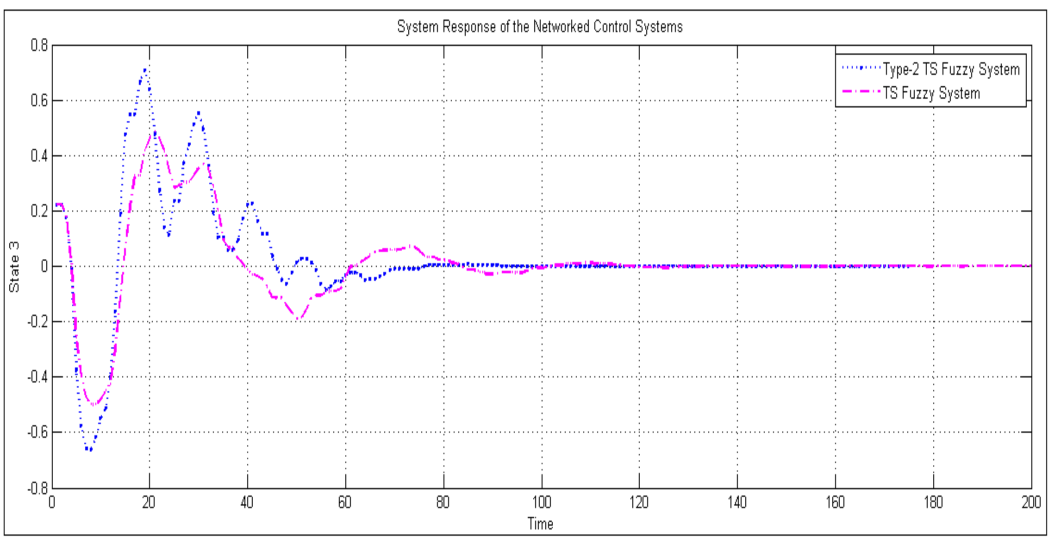

Figure 4.13: Type-2 TS Fuzzy System vs TS Fuzzy System

The response of the system is plotted for two cases i.e., for $\phi_1 = 1.2$, $\phi_2 = 2$ and $\phi_1 = 10$, $\phi_2 = 30$. The response of the system is better for the first case as the settling time for all the states is less (i.e., 60 sec) than compared to the second case (i.e., 80 sec).The response is also plotted for $\phi_1 = 0.1$, $\phi_2 = 0.3$ but the system response was unstable.

The response of the Type-2 TS FLC for NCS is then compared to the TS Fuzzy system, the simulation results show that the response of the Type-2 TS Fuzzy system is better than TS Fuzzy system. The settling time and maximum peak overshoot for Type 2 FLC was much less than TS Fuzzy system for both the cases. In both the cases, the settling time for all the states for Type-2 FLC was around 60-90 sec whereas the settling time for TS Fuzzy System was around 120-140 sec.

The response of the system was then plotted for different delays to understand the response change with the change in delays.

The response is plotted first for exponential delay, choosing delay as $\phi(t) = 0.1e^{-t}$. The response is shown in the Figure 4-14.

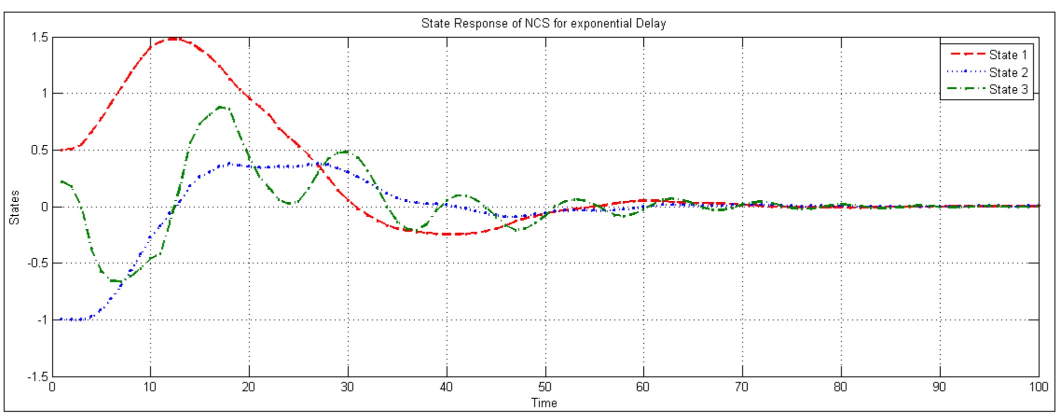

Figure 4.14: State Response for Exponential Delay

It can be inferred from the plot that the response for exponential delay is sluggish i.e., the settling time is 75 sec which is more than for the other delay i.e., sine which had a settling time of 70 sec.

Now, the response is plotted for step delay. The delay is considered for two cases i.e., unit step delay and step delay with step size of 5. The response is as shown in the Figure 4-15, Figure 4-16.

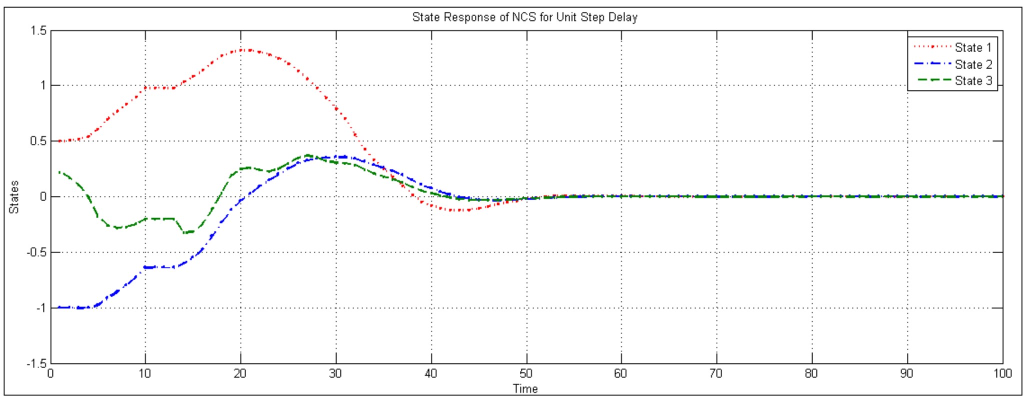

Figure 4.15: State Response of NCS for Unit Step Delay

From the state response of the system for unit step delay it can be inferred that the settling time is much less i.e., nearly 50 sec and the maximum peak overshoot for the state 1 is also less i.e., nearly 1.3.

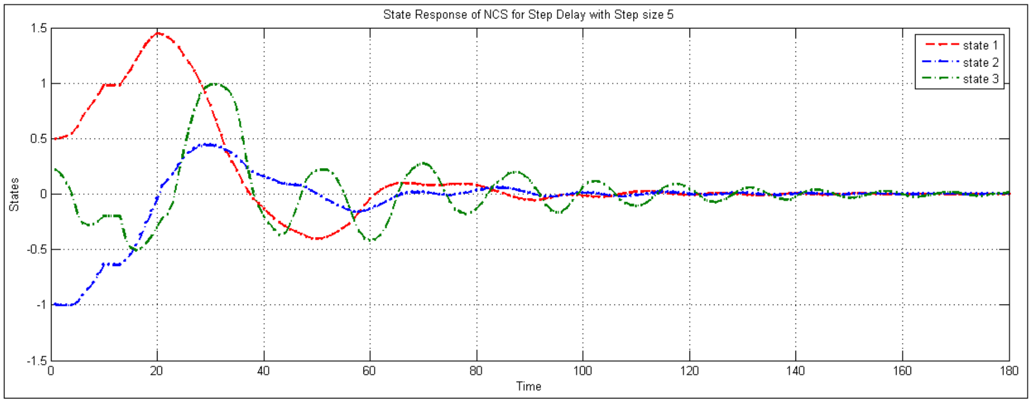

Figure 4.16: State Response of NCS for Step Delay with Step size 5

From the state response of the system for step delay with step size of 5 it can be inferred that the settling time has increased drastically i.e., nearly 180 sec.

Now we consider a third case where $\phi_1 = 1$ and $\phi_2 = 10$

Case 3:

For $\phi_1 = 1,\ \phi_2 = 10$ we get a different set of controller gains can be obtained as,

$$K_1 = \begin{bmatrix} -0.5064 & 0.1353 & 0.4071 \end{bmatrix}$$

$$K_2 = \begin{bmatrix} -1.7367 & -0.6199 & 2.6211 \end{bmatrix}$$

$$K_3 = \begin{bmatrix} -0.0338 & -0.0495 & 0.1108 \end{bmatrix}$$

$$L_1 = \begin{bmatrix} 46.2517 \\ 47.2190 \\ 48.2905 \end{bmatrix},\ L_2 = \begin{bmatrix} 38.7136 \\ 38.9012 \\ 40.3141 \end{bmatrix},\ L_3 = \begin{bmatrix} 35.7992 \\ 35.8920 \\ 37.0773 \end{bmatrix},$$

The simulation results are shown in Figures 4-17.

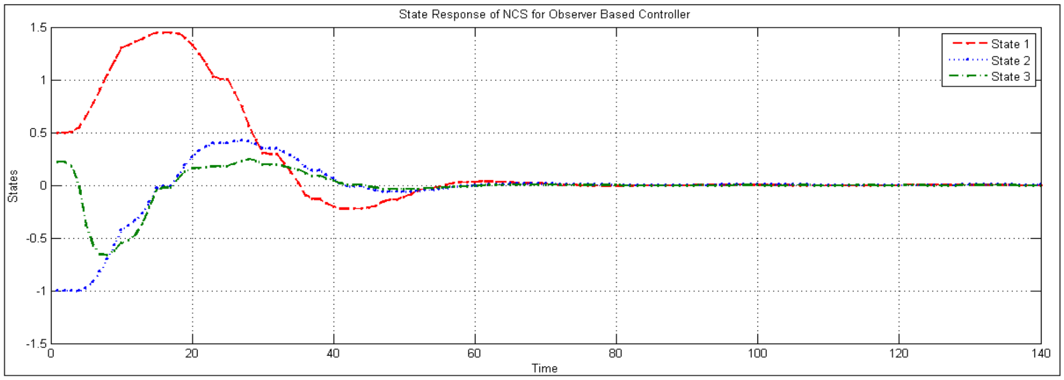

Figure 4.17: System Response for the Observer based Controller

From the system response it can be inferred that the settling time of the response is quite similar to case 1 but better than for the second case that had a settling time around 70 sec. So the system takes much less time to reach the set point value.

The response of the system was then plotted for different delays to understand the response change with the change in delays.

The response is plotted first for exponential delay, choosing delay as $\phi(t) = 0.1e^{-t}$. The response is shown in the Figure 4-18.

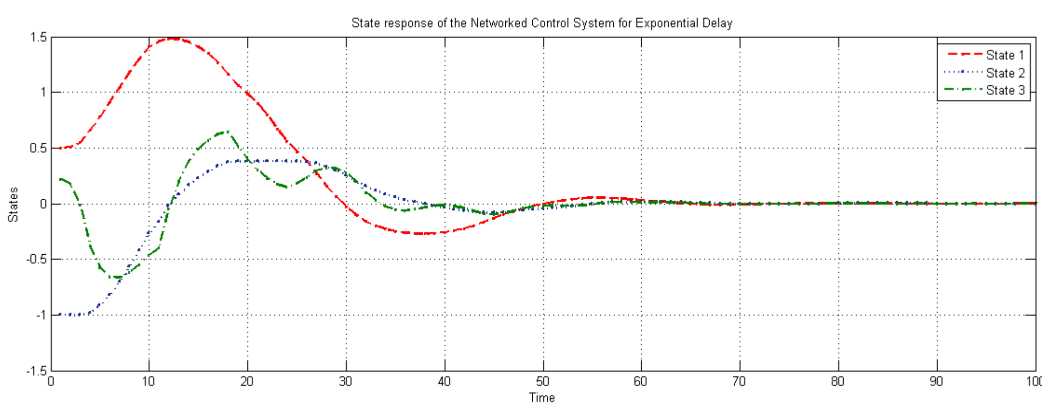

Figure 4.18: State Response for Exponential Delay

It can be inferred from the plot that the response for exponential delay is much faster i.e., the settling time is 60 sec which is less than for the other delay i.e., sine which had a settling time of 70 sec.

Now, the response is plotted for step delay. The delay is considered for two cases i.e., unit step delay and step delay with step size of 5. The response is as shown in the Figure 4-19, Figure 4-20.

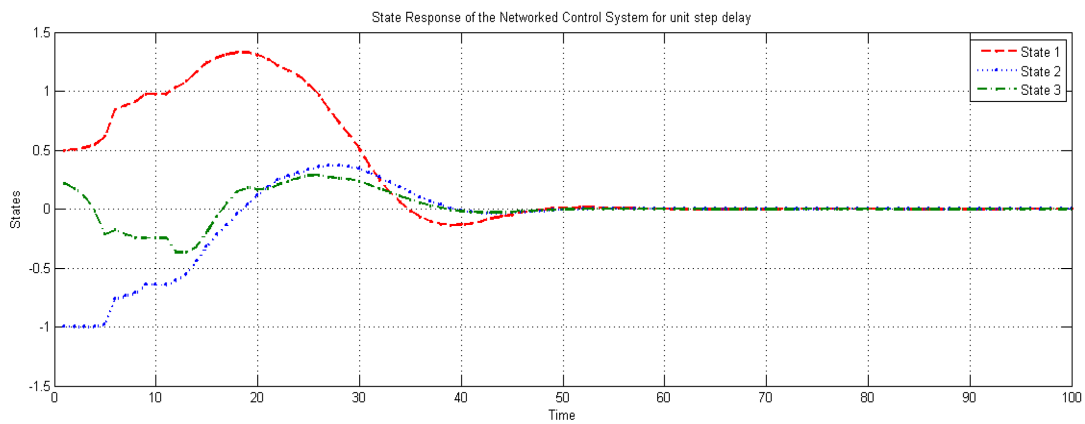

Figure 4.19: State Response of the NCS for unit Step delay

From the state response of the system for unit step delay it can be inferred that the settling time is much less i.e., nearly 50 sec and the maximum peak overshoot for the state 1 is also less i.e., nearly 1.3.

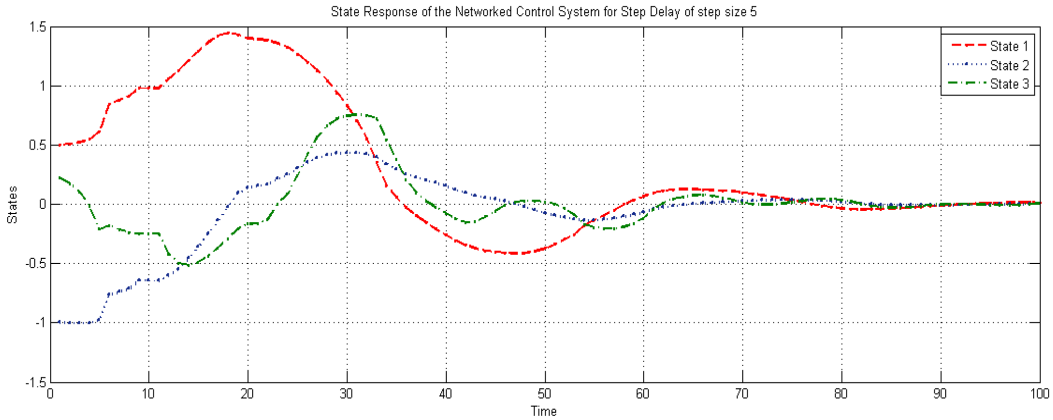

Figure 4.20: State Response of the NCS for Step delay of step size 5

From the state response of the system for step delay with step size of 5 it can be inferred that the settling time has increased drastically i.e., nearly 100 sec.

Comparison of Observer Based Feedback Control with that of State Feedback Control Design and the Control Design in [43]

The results of the observer based controller design explained in this chapter are compared with that of the state feedback control design in previous chapter and the control design results in [43]. The results are shown in Figures 4-21, 4-22, 4-23.

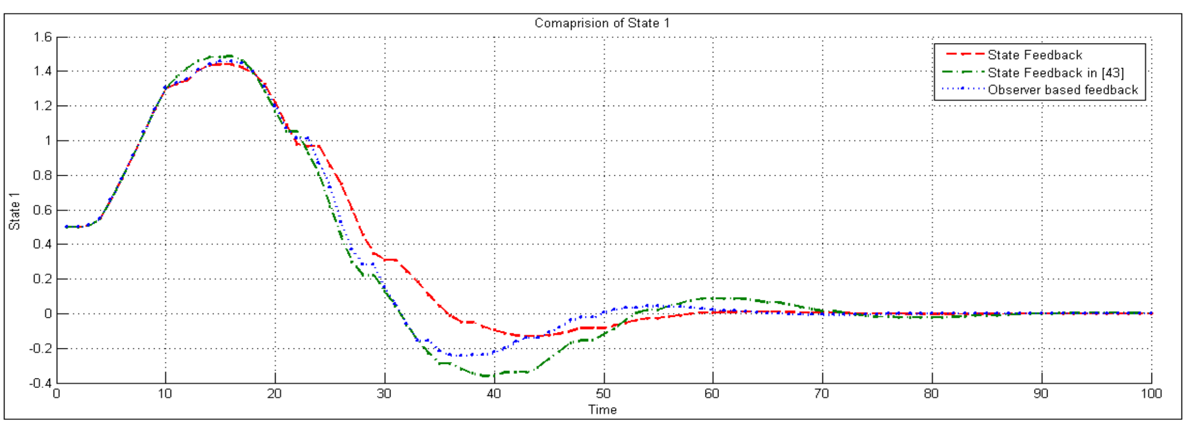

Figure 4.21: Comparison of State Feedback Controller Vs Observer Based for State 1

It can be inferred from the above Figure 4-21 that, the response of the observer based controller developed in this thesis is much better than the response of the state feedback control explained in chapter 3and the feedback control developed in [43]. The settling time for observer based control is 60sec and the settling time for state feedback control is around 65 sec and 95 sec in the case of the state feedback control response in [43].

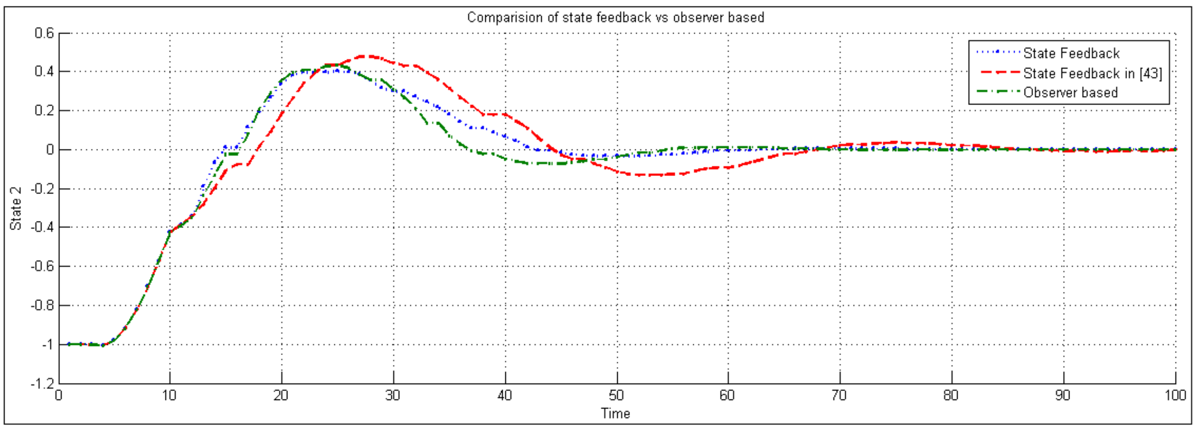

Figure 4.22: Comparison of State Feedback Controller Vs Observer Based for State 2

It can be inferred from the above Figure 4-22 that, the response of the observer based controller developed in this thesis is much better than the response of the state feedback control explained in chapter 3and the feedback control developed in [43]. The settling time for observer based control is 60sec and the settling time for state feedback control is around 65 sec and 95 sec in the case of the state feedback control response in [43].

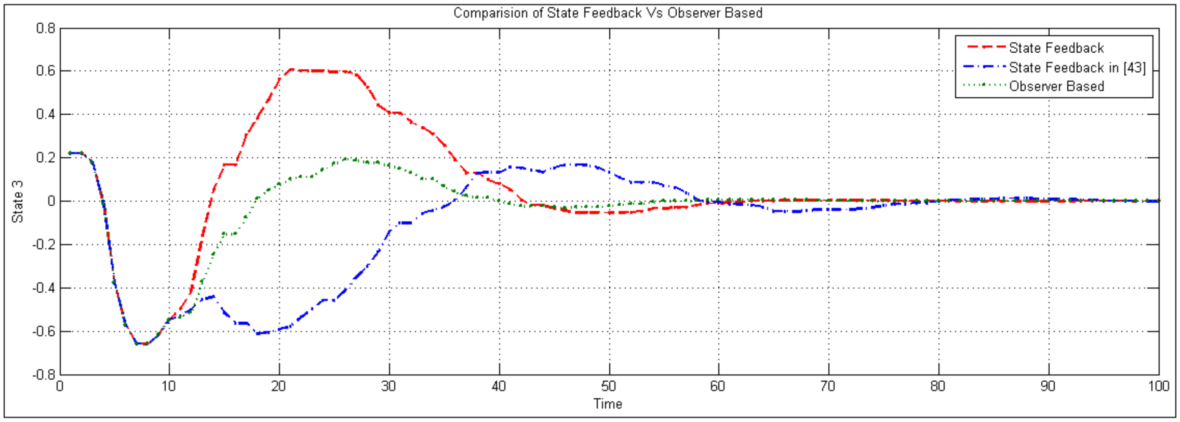

Figure 4.23: Comparison of State Feedback Controller Vs Observer Based for State 3

It can be inferred from the above Figure 4-23 that, the response of the observer based controller developed in this thesis is much better than the response of the state feedback control explained in chapter 3and the feedback control developed in [43]. The settling time for observer based control is 60sec and the settling time for state feedback control is around 65 sec and 95 sec in the case of the state feedback control response in [43].

4.4 Conclusions

This chapter discusses the design of an observer based Type-2 Fuzzy Logic Controller subjected to delays based on Lyapunov-Krasovskii theory. Numerical simulations have also been used to illustrate the developed technique. We can also extend the results to include data packet dropouts and also to incorporate noise so as to address the robust control problem. The results of the Type-2 TS FLC were plotted for two cases and it can be concluded that the response was better for first case than compared to second case. The results of the Type-2 FLC are compared with that of the TS Fuzzy System. It can be inferred from the results that the response for the system to become stable for the Type-2

TS FLC was much faster than that of TS FLC as the settling time for Type-2 FLC was much less. The simulations prove the effectiveness of the proposed controller.

Chapter 5

CONCLUSIONS & FUTURE WORK

To summarize the work presented in the thesis, a novel observer based control design technique has been proposed with perspective of improving the effectiveness of control of Networked Control System. The observer based controller is designed with a Type-2 Fuzzy Logic Control System. The effectiveness of the approach is proved by comparing the results with that of the TS Fuzzy System.

The most recent developments in Networked Control dealt with the designing of various control techniques to control the flow of information through the network. Various assumptions are made in order to solve the control problem. Various factors could lead to non-uniform behavior of the network ranging from ambient temperature to network traffic and aging of communication equipment.

In the first part we design a Type-2 Fuzzy Logic based State Feedback Control for a nonlinear continuous Network Control System with delays. The delays are considered for both actuator and sensor part of the communication network. Both the delays are assumed to be equal. The behavior of the system is then compared with the TS fuzzy Logic based State Feedback Control for NCS.

We extended the work of Chwan-Lu Tseng et al [43] by developing an improved stabilizing control algorithm to estimate the states and control input through the construction of an augmented system where the original control input was regarded as a new state. The Lyapunov Krasovskii functional was used to obtain the stability conditions, which can be expressed in the form of LMIs. The measurement and actuation delays were considered using random processes. The observer-based controller was designed to stabilize the networked system and the developed stability conditions were represented in the form of a convex optimization problem and the results were tested by simulation. The simulations revealed that the newly developed control strategy provided faster and effective response in stabilizing the Networked Control System.

In the next chapter, we designed an observer based on the theory developed by Mourad Kchao et al. [7]. We extended the state feedback control design to include observer in the model. Simulations were carried out to prove the effectiveness of the control design.

The area of networked control is very vast and may have a lot of potential for further research to be done. Hence our work in this thesis has a great potential to be expanded in various directions. Suggestions for future research would be

- In designing the controller for NCS we considered delays in measurement and actuation channel. Data packet dropouts can also be considered for designing the Type-2 FLC based controller.
- Many other controllers can be designed for solving the control problem.

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